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PROFESSOR L. FAGE : *Institut d'Oceanographie, 195 Rue St. Jacques, Paris 5, France*

DR. M. N. HILL : *Department of Geodesy and Geophysics, Cambridge University, Madingley Rise, Madingley Rd., Cambridge*

DR. MARY SEARS : *Woods Hole Oceanographic Institution, Woods Hole, Mass., U.S.A.*

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Measurements of light penetration in Relation to Vertical Migration and Records of Luminescence of Deep-Sea Animals

GEORGE L. CLARKE and RICHARD H. BACKUS

Abstract—Direct measurements of the intensity of light at the levels of certain deep scattering layers were made using a bathyphotometer capable of responding to illumination as low as 10^{-7} μw/cm^2 or about 10^{-12} of full sunlight. The vertical migration of the scattering layers was recorded by means of an echo sounder. During the middle of the day a single scattering layer was found and the top of this remained below the 0·01-μw/cm^2 isolume. In the late afternoon the layer split into two and both parts rose more rapidly than the isolumes with the result that at sunset the top of the upper layer was 40 m above the 0·1-μw/cm^2 isolume. Reactions other than the following of a certain light intensity were thus involved in the vertical migration of these layers.

Flashes from luminescent animals detected by the bathyphotometer were recorded on a Brush pen recorder. The intensity and frequency of luminescent flashes varied greatly with depth and with time and presented differing patterns in coastal and slope waters.

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INTRODUCTION

MOST pelagic animals in the ocean and in lakes are limited in their vertical distribution to definite ranges of depth, and many kinds of zooplankton and fishes are known to undertake characteristic vertical migrations downward to lower levels in the early morning with a return to higher levels in the evening. This diurnal migration appears to be more closely correlated with changes in the strength of the light penetrating from the surface than with any other known factor of the environment (CUSHING, 1951). In certain instances in which the migration was confined to relatively shallow depths, measurements of the illumination in the water have been made at the same time that the vertical distribution of the animal populations was determined by means of plankton hauls (CLARKE, 1933, 1934a). However, photometers of the usual type containing photovoltaic cells are not reliable for the measurement of intensities less than about 0·01 per cent of sunlight. Accordingly, with this type of photometer, the relation between light as an ecological factor and the activities of migrating animals cannot be directly investigated at depths greater than about 60 to 80 m even in clear waters (CLARKE, 1954). At greater depths or in less transparent water a more sensitive photometer is required, or else reliance must be placed on an extrapolation of the diminution of light assuming that the extinction rate in the deeper water is the same as that actually measured near the surface – an assumption which may lead to highly erroneous results (KAMPA, 1955).

Off the continental shelf, net hauls have shown that certain species of Crustacea carry out diurnal migrations the lower limits of which are as great as 800 m (WATERMAN *et al.*, 1939). In addition, echo sounder records have revealed the widespread occurrence of " deep scattering layers," commonly at depths of 400 to 600 m during the daytime but also sometimes as deep as 1,000 m (MOORE, 1950). These layers typically migrate vertically several hundred metres each day. Although the kinds of animals primarily responsible for these sound-scattering layers are not precisely known, it seems probable that euphausids and fishes are involved in at least some

of these layers (MOORE, 1950; BODEN, 1950; TUCKER, 1951; MARSHALL, 1951; HERSEY and BACKUS, 1954). No doubt concentrations of other animals, some of which do not reflect sufficient sound to be recorded by present equipment, are living at various levels in the ocean and are carrying out similar or perhaps even more extensive migrations, as yet undetected.

The construction of photometers containing extremely sensitive photomultiplier tubes has made possible the direct measurement of light at depths at which the deep scattering layers are found in the oceans and hence permit a more exact study of the role of light in the control of diurnal migration. Observations with the bathyphotometer (CLARKE and WERTHEIM, 1956) not only provided measurements of transparency to depths as great as 610 m but also revealed the fact that luminescent flashing of deep-sea animals may be of an intensity comparable to the daylight reaching the lower part of this range. Off southern California, KAMPA and BODEN (1954) undertook simultaneous observations of illumination and the movements of a sound-scattering layer. The observations reported in the present paper were made in the slope water southeast of New York and yielded somewhat different results. Our direct reading bathyphotometer was employed during the day to measure the light penetrating from the surface to the level of the scattering layers as observed on the echo sounder. In addition, during the night the bathyphotometer and strip recorder were used to compare the strength and frequency of the flashes of luminescent animals at various depths as well as to record the changes with time of the luminescence at the same level.

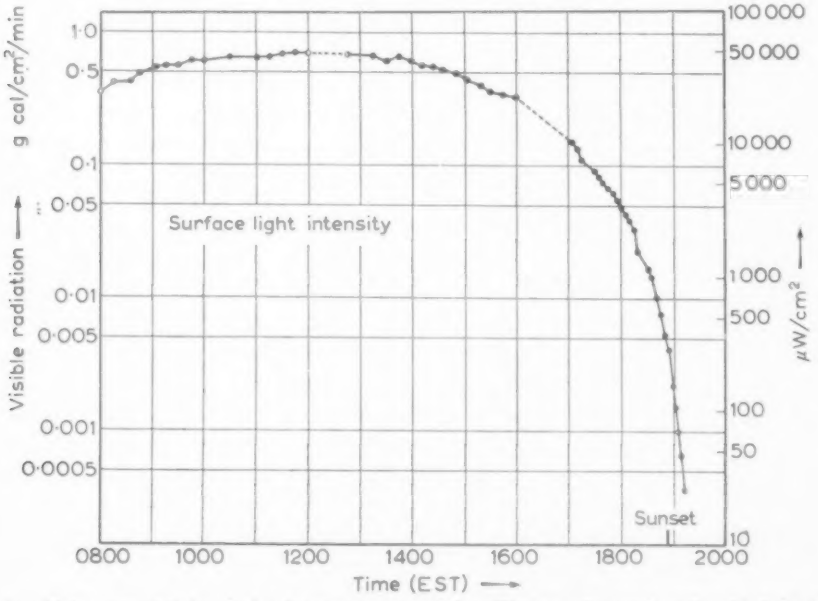

Fig. 1. Light recorded by deck photometer containing Weston photronic cell. 21 July 1955. Position 38°21'N, 69°09'W.

SUBMARINE DAYLIGHT AND VERTICAL MIGRATION

Observations. The relation between intensity of illumination and the vertical migrations of certain scattering layers was investigated from the research vessel

Atlantis on July 20 and 21, 1955 at the stations 200 miles SE of New York for which transparency values were reported by CLARKE and WERTHEIM (1956, Table 1, Series 23, 24 and 25). Since the stations were only about four miles apart with closely similar surface light, transparency, and scattering layer behaviour, the results of the two days' observations are considered together.

During the day-time periods measurement of the light at the sea surface were made by means of a deck photometer containing a Weston photronic cell provided with a diffusing surface of semitranslucent plexiglas and mounted in gimbals. The record of surface light intensity reveals the relatively steady illumination during the middle of the day and the precipitous drop near sunset (Fig. 1). From this record and measurements of transparency to a depth of 554 m (CLARKE and WERTHEIM, 1956) a family of curves was drawn showing the depth of the isolumes ranging from 10,000 to 0·00001 $\mu w/cm^2$ (Fig. 2). In conformity with the changes in surface light the isolumes remain at a relatively constant depth during the middle of the day but later move rapidly upward especially at sunset.

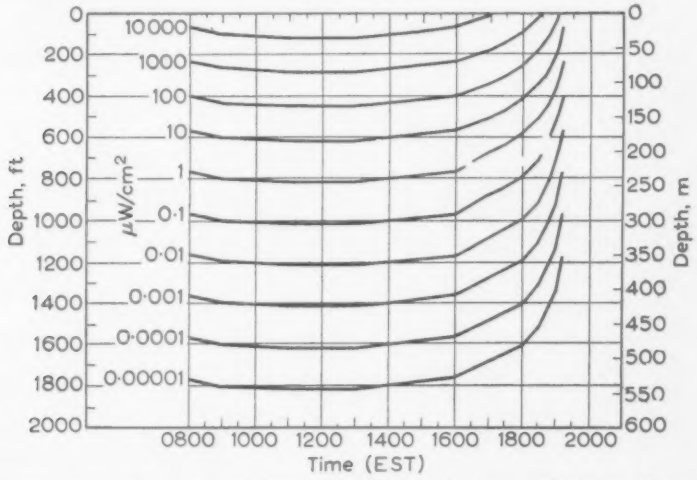

Fig. 2. Isolumes for 21 July calculated from surface light using the extinction coefficient measured for the water column.

Scattering layer observations were made with an Edo Corporation UQN/1B 12 kc transducer and electronic system coupled with a high-resolution recorder (KNOTT and HERSEY, 1956). Sample sections of the record obtained on 21 July (Figs. 3 and 4) show the presence of a single pronounced scattering layer the top of which was found at a depth of about 300 m at 1700 hours. This layer moved upward slowly during the first hour and then at 1810 began to divide into two layers.

To obtain a direct measure of the light at the level of the scattering layers the bathyphotometer was lowered beginning at 1700 hours. The echoes from the bathyphotometer were immediately discernible on the echo-sounder record in the ship's laboratory and this echo sequence is seen as a downwardly sloping trace labelled " photometer " (Fig. 3). When the bathyphotometer was observed to have reached the level of the top of the scattering layer, lowering was halted and measurements of light intensity were begun. By 1836 hours two scattering layers were apparent

and the upper one had moved to a position above the photometer. Accordingly, the instrument was raised until its level again conformed with the top of the upper layer. In the succeeding 20 minutes this scattering layer moved up past the photometer and soon thereafter the echoes from it became diffuse and merged with the surface " noise."

The bathyphotometer was lowered again at 1854 hours until it reached the level of the top of the lower scattering layer. At this time the lower layer had become dense and was moving rapidly toward the surface. As the trace from this layer moved up past the photometer (Fig. 4), the instrument was again raised, and subsequently this process was repeated until about 1927 hours when the trace merged with the surface " noise."

By the foregoing procedure the moments could be directly observed on the echo sounder when the depth of the photometer coincided with the depth of the scattering layer under study, and the illumination at that depth immediately determined by readings made in the ship's laboratory. From these direct measurements the depths of the 0·1- and 0·01-μw/cm^2 isolumes were calculated using the values of the extinction coefficient of the water measured earlier in the day. In this way the position of these isolumes, which were never far from the depths of the attendant photometer readings, was determined with greater assurance than if calculations had been made from the surface light values.

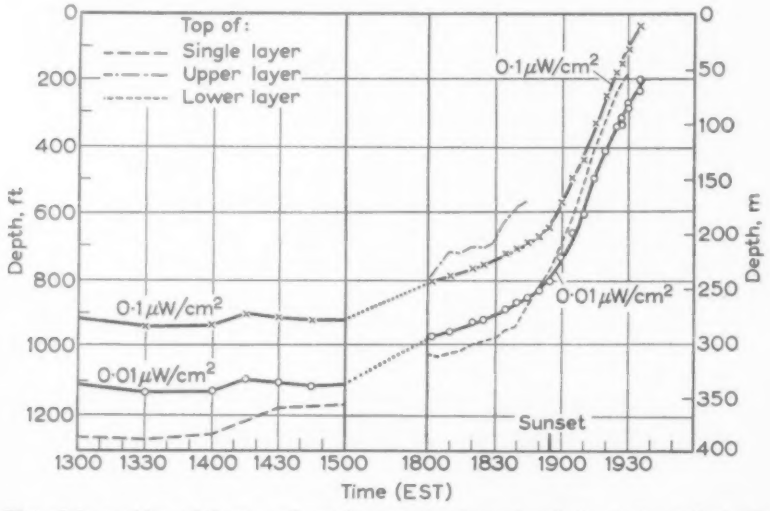

Fig. 5. Plot of the position of the tops of certain scattering layers in relation to the indicated isolumes for the indicated periods on 20 July.

The changes in level of the scattering layers have been compared with the changes in the intensity of illumination in the water for certain periods on 20 July (Fig. 5). During the afternoon only a single scattering layer was discernible. The top of this layer was at 390 m at 1300 hours and about 50 m below the 0·01-μw/cm^2 isolume. By 1500 hours the layer had risen to 355 m although the isolume had not changed position appreciably.

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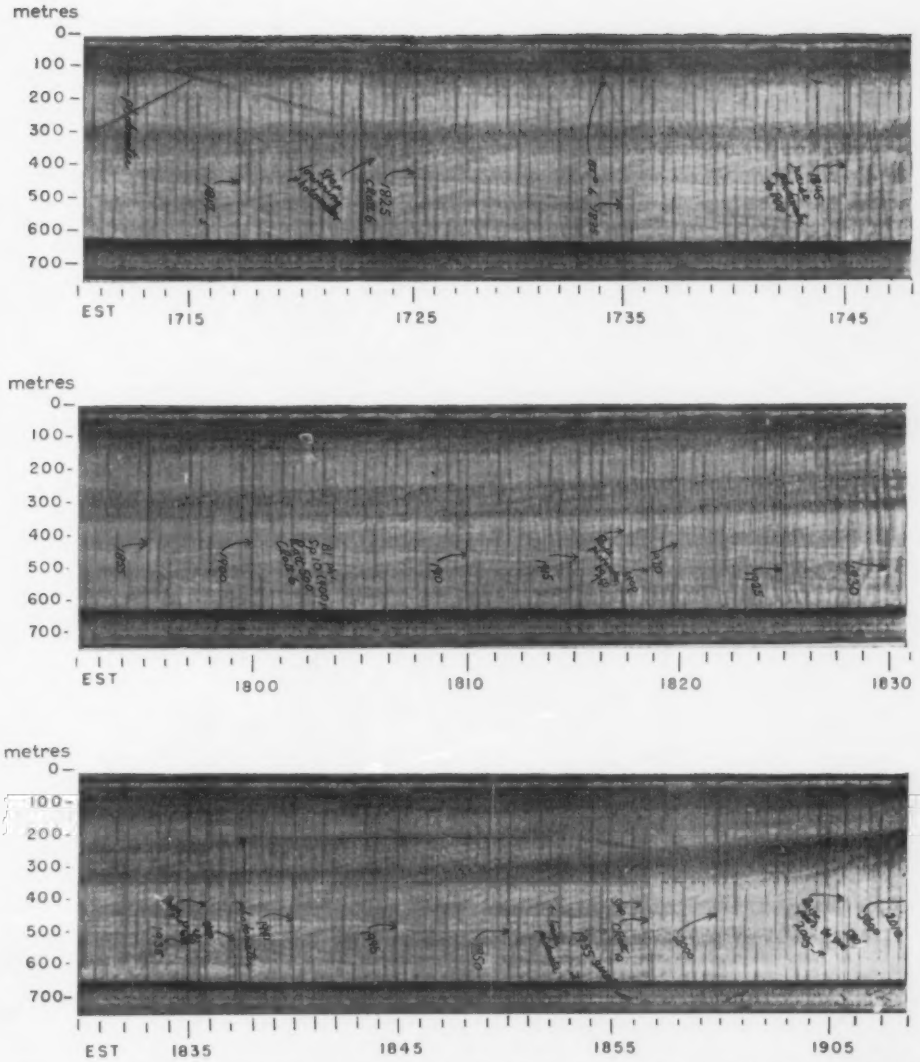

Fig. 3. Echo-sounder record on 21 July for the hours indicated (Daylight Saving Time on the record and Eastern Standard Time in the bottom margins). Zero depth in this and the succeeding figure represents the depth of the transducer which is about 5·5 m below the surface. Near-surface reverberation appears as a broad black band at top. The bottom echoes show as a heavy black band near the lower margin during the fifth traverse of the record and indicate a depth of 3,840 m.

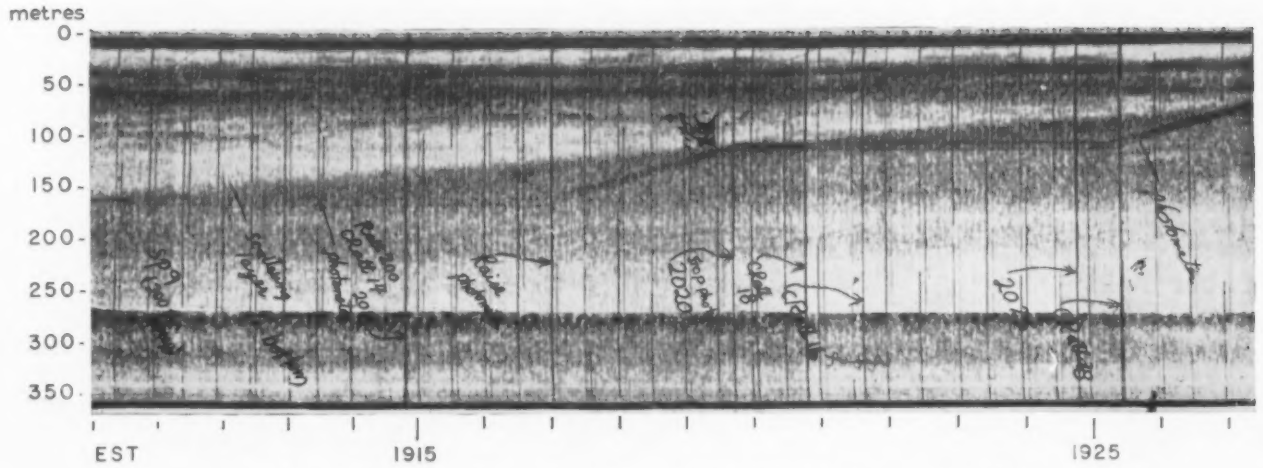

Fig. 4. Continuation of the echo-sounder record on 21 July, but with an enlarged scale.

During the evening two scattering layers were recorded. At 1800 hours the top of the upper layer was found at 240 m and corresponded in depth very closely to the position of the 0·1-μw/cm^2 isolume. At the same time the top of the lower layer was observed at 315 m which was about 15 m below the level of the 0·01-μw/cm^2 isolume. The upper scattering layer rose rapidly, although irregularly, from 1800 to 1845 hours at which time it was found at a depth of 170 m or 40 m above the 0·1-μw/cm^2 isolume. The lower scattering layer moved upward slowly at first but more rapidly after 1840 hours, rising from 286 to 54 m in the ensuing 50 minutes, or at an average rate of 4·6 m vertical rise per minute.

A similar comparison for 21 July showed that the top of the upper scattering layer, although fluctuating in position, followed in a general way the upward movement of the 0·1-μw/cm^2 isolume from 1730 to 1830 hours (Fig. 6). At 1800 the depth of the layer and the isolume was 250 m, as on the previous evening. In the 20 minutes following 1830 the upper scattering layer moved to a position 40 m above the isolume. The densest portion of the upper scattering layer was located midway between the isolumes at 1730 hours but moved to a position above the 0·1-μw/cm^2 isolume at 1840.

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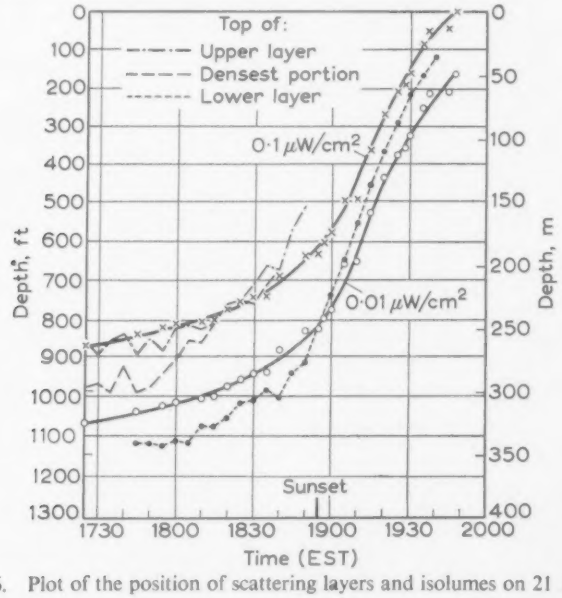

Fig. 6. Plot of the position of scattering layers and isolumes on 21 July.

At 1800 hours on 21 July the lower scattering layer was found at 340 m, or 30 m below the 0·01-μw/cm^2 isolume. It was thus 30 m below its depth at the same time on the previous evening, whereas the isolume was only 10 m below its previous level. As before the lower scattering layer moved gradually upward during the next 40 minutes, parallelling the rise of the isolume. At about the same time as on the previous evening the scattering layer accelerated its upward migration, reaching a depth of 65 m at 1930 with an average rate of rise of 4·4 m per minute. As before, this scattering layer rose more rapidly than the 0·01-μw/cm^2 isolume after 1830 hours and at 1940 was located at 36 m, or 30 m above the isolume.

Discussion. The general features of the depth distribution and migration of the scattering layers observed in this investigation are essentially similar to observations earlier reported. The separation of the principal layer into two layers during the sunset ascent has been reported by BODEN (1950) and by TUCKER (1951). DIETZ (1948) reported a layer that was double during the morning descent but remained unsplit during the evening migration. TUCKER (1951) associated shallower, less intense sound scattering with euphausids and deeper, more intense scattering with fishes, but he does not state whether he considers this conclusion to apply to layers which split during the evening and morning migrations.

The present observations on light made simultaneously with the records of the vertical distribution of the scattering layers make possible a further study of the manner in which light acts to control the diurnal migration. On the two successive days the relation with time of ascent, depth, and light intensity was remarkably similar for both upper and lower scattering layers. This suggests that the control of vertical position may be rather precise, and also uniform over considerable areas, since the ship had drifted for several miles between the two evening observations.

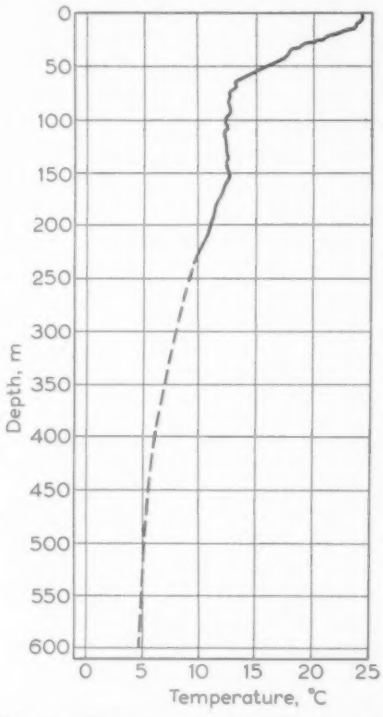

Fig. 7. Temperature section for 21 July, 1955. Solid line from bathythermograph slide made at the time; broken line from measurements taken in previous years in this area and season. Bathythermograms made on 20 July 1955 show essentially the same temperature structure in the upper 240 m.

Our observations agree with previous findings in showing that the diurnally migrating plankton tends in general to follow the vertical movements of certain isolumes (CLARKE, 1934a; WATERMAN *et al.*, 1939; MOORE, 1950; KAMPA and BODEN, 1954). However, the details of the relation with light and the degree of modification of behaviour that is brought about by other factors vary in different instances. In the Gulf of Maine the upward migration of copepods was found to be stopped by the summer thermocline on one occasion (CLARKE, 1933) but not on another occasion (CLARKE, 1934a). Temperature, and perhaps also pressure, may affect the vertical position of zooplankton (MOORE, 1955). Recent laboratory studies of the effects of light intensity on the phototaxis and photokinesis of certain plankton animals are summarized by HARRIS and WOLFE (1955), and modifications of these reactions by changes in *p*H and other factors have been investigated by E. R. BAYLOR (private communication) and others.

In the locality where the present observations were made the temperature gradient apparently did not cause a significant change in the pattern of the vertical migration of the scattering layers. The temperature profile (Fig. 7) showed a sharp decline

from 24°C near the surface to 13°C at 65 m. The temperature remained essentially unchanged from this depth to 150 m and then gradually dropped off to about 4·5°C at 600 m. During the two evening observations reported here the deeper scattering layer was observed to move upward without an abrupt change of rate from about 300 m to 55 m and 36 m respectively, thus undergoing a temperature change of 8°C or more. The animals may have continued to rise still nearer to the surface, but if so, their echoes were obscured by the surface " noise."

The present observations indicate the extent to which the migrating animals tend to maintain themselves at an " optimal " intensity of light – that is, one at which they tend to congregate by a phototactic, photokinetic, or other reaction. During the early afternoon of 20 July the top of the single scattering layer was located at a depth where the light was little more than 0·001-μw/cm^2 but the layer moved upward toward the 0·01-μw/cm^2 isolume at 1430 hours (Fig. 5). Since the two scattering layers distinguishable at a later hour appear to have arisen by a continuous process from the single layer, it seems probable that the two sets of animals in the separated layers had already been present in the single layer. The animals that formed the top of the single layer presumably continued in the vanguard of the upward moving population and formed the top of the upper layer. If this was the case, then these animals crossed the isolumes for 0·01 and 0·1-μw/cm^2 and continued moving upward into light which was more than 100 times brighter than that existing at their midday level. Assuming that the animals in the lower part of the single scattering layer formed the lower of the two separated layers, these individuals similarly moved up into much more intense illumination. Thus both scattering layers moved upward faster than the isolumes did, particularly in the period beginning about one half hour before sunset.

The same tendency for the animals to accelerate their migration and to move into brighter light was observed on the evening of 21 July (Fig. 6). On this occasion the depth of the top of the densest portion of the upper scattering layer was also plotted during the period when this differed markedly from the depth of the uppermost limit of this layer. The depth of the top of the densest portion changed from about midway between the depths of the tops of the upper and lower layers to a level nearly the same as the top of the upper layer. This change might have resulted from a shift in the concentration of the animals in the upper layer or from the presence of more than one type of animal in this layer.

Frequently zooplankton populations have been reported to descend to their maximum depths early in the day and to rise to levels nearer the surface during midday or early afternoon where light intensity is higher. This is interpretated as a manifestation of light adaptation resulting in an increase in the intensity of illumination which is reacted to as optimal by the animals concerned. As the isolumes move toward the surface during the evening, those animal populations which tend to congregate at a certain intensity would move upward at a corresponding rate provided that their powers of locomotion were sufficient to enable them to keep up. Off southern California during the early part of the migration the scattering layer lagged behind the ascending isolume with which it had been associated earlier in the afternoon (KAMPA and BODEN, 1954). During this period the upward movement was slow and there seems no reason to believe that the animals could not keep up; rather the investigators suggest that the threshold intensity of migration may be slightly

lower than the intensity of the optimal illumination. The fact that the receiving surface of the photometer used by KAMPA and BODEN was vertical may have introduced some differences in the light values recorded, as compared with the changes in underwater intensities recorded when employing the usual horizontal receiving surface (CLARKE and WERTHEIM, 1956).

During the period of most rapid ascent observed by KAMPA and BODEN the scattering layer and the isolume with which it was associated moved upward together at the rate of 5·1 m per minute. This rate of rise is about the same as that observed in the present investigation but considerably higher than values of about 1 m per minute reported by CLARKE (1934b) for copepod populations in the Gulf of Maine and by HARDY and BAINBRIDGE (1954). Scatterers that can move upwards at rates faster than 4 m/minute are presumably strong swimmers such as fishes or the larger crustaceans.

If we accept the idea that photic reactions cause animal populations to move away from high light intensities during the day and that their day-time level is determined by that intensity which causes no negative response, we should not expect the animals to move upward faster than their optimal illumination and thus pass into brighter light. Since such behaviour was clearly observed in the present investigation, we must conclude that other factors have entered the picture. One possible explanation is that the upward migration is initiated primarily by the *change* in light and that once the stimulus has been received from a sufficient reduction in light, the animals swim steadily toward the surface even though this means moving into higher intensities. This type of response to a reduction in light has been observed in the laboratory particularly with fresh-water plankton, such as *Daphnia* (CLARKE, 1932; HARRIS and WOLFE, 1955). The present observations thus provide additional evidence for the occurrence in vertically migrating animals of tactic or kinetic responses that may considerably modify the general tendency to remain at the level of a certain intensity of illumination.

RECORDS OF LUMINESCENCE

Observations. During the measurements of transparency made in July 1955 (CLARKE and WERTHEIM, 1956) flashes of light were observed during the day-time at levels near the maximum depth attained (610 m) and at all levels down to 610 m at night but particularly at the deeper levels. These flashes are interpreted as the luminescent activity of fishes or invertebrates and may be due to intermittent discharges of the photophores of certain animals or may result from the movement of steadily luminescing forms past the receiving surface of the photometer. In order to determine in a preliminary way the variation in the amount and type of luminescence at different depths and at different times, observations were made from the research vessel *Bear* on 6 September 1955 in the coastal water about 40 miles south of Martha's Vineyard, and on 8 September 80 miles farther south in the slope water between the continental shelf and the Gulf Stream and about 80 miles northwest of the area studied on 20 and 21 July, 1955.

The records of flashes were made by connecting an Edin AC amplifier in parallel with the microammeter reporting the light response of the bathyphotometer. The amplifier was in turn connected to a Brush pen recorder (CLARKE and WERTHEIM, 1956, Fig. 2). This system was used to resolve more satisfactorily the flashes originally

observed on the microammeter and to obtain a graphical record. It was intended only to show the frequency of occurrence of flashes brighter than the background. Since the recorder did not report the level of steady background illumination, little

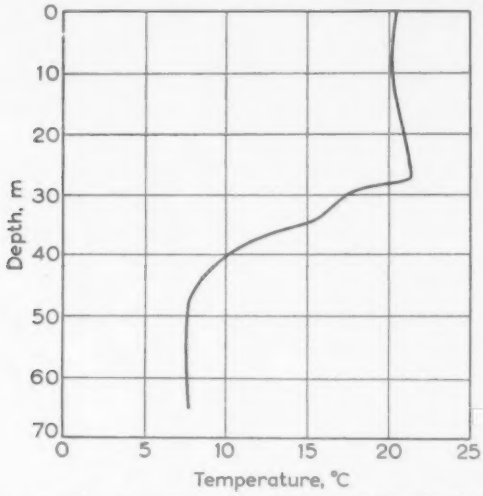

Fig. 8. Temperature section for 6 September 1955, made from bathythermograph slide.

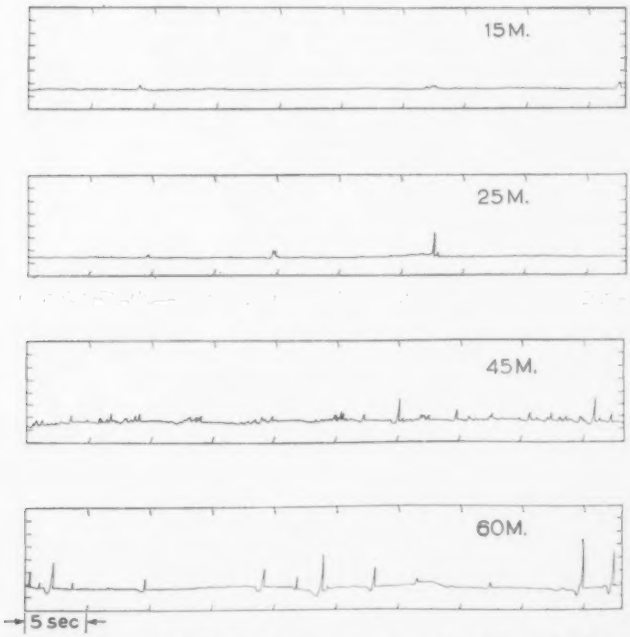

Fig. 9. Sections of records, made with Brush pen recorder, of luminescent flashes at the indicated depths at 1915-2035 EST. 6 September 1955, position: 40°37′N, 71°03′W. No moon or stars visible. (Bathyphotometer circuit voltage: Position 9, scale 50). Abscissa: time; ordinates: see text.

can be said about the relative intensity of the flashes recorded. In any event the actual relative intensities of the sources could not be deduced since their distances

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from the photometer are unknown. The background illumination is probably composed of numerous flashes dimmer than those recorded but might consist of light from continuously luminescing organisms. Because of the relationship between the band pass of the recording system and the duration of the flashes the recorder has given a fairly accurate portrayal of the "shape" of the flashes.

The coastal water station was occupied early in the evening of 6 September in 70 m of water. A bathythermogram made at this station showed that the temperature was relatively uniform in the upper 28 m at 20·2 to 21·°5C, dropped in a sharp thermocline to 7·5°C at 48 m, and thence remained about the same to the bottom (Fig. 8). Strip records of luminescent flashing were made at 15, 25, 45, and 60 m (Fig. 9). At 15 m the flashes typically were small and infrequent. Somewhat more luminescent activity was detected at 25 m. Animals near the bottom of the thermocline at 45 m produced very frequent but small flashes, whereas at 60 m irregularly spaced medium to large flashes were recorded.

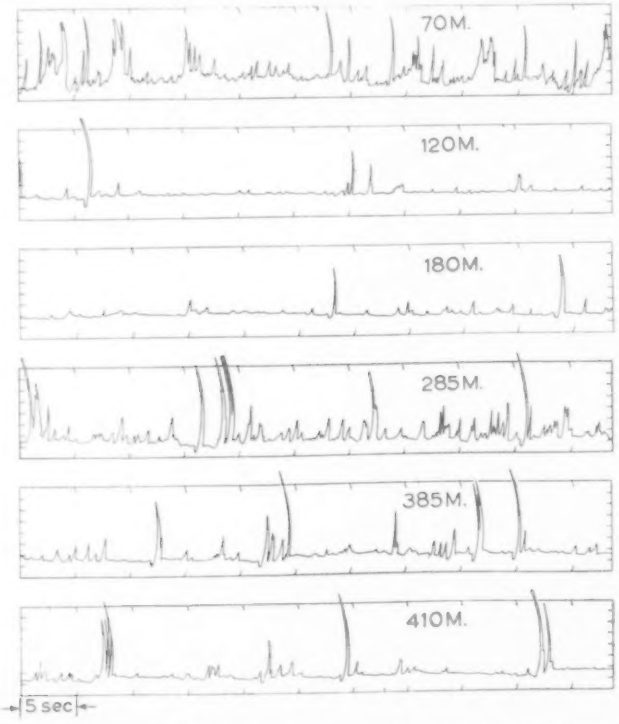

Fig. 10. Sections of record made with Brush pen recorder showing luminescent flashes at the indicated depths at 1945-2130 EST., 8 September 1955, position: 39°23′N, 70°16′W. No moon but faint stars visible. (Bathyphotometer circuit: voltage position 9, scale 5). Abscissa: time; ordinates; see text.

The station in the slope water was occupied at about the same time in the evening of 8 September in about 2,560 m of water. The thermal structure in the upper 600 m was similar to that recorded for the slope water station occupied on 21 July. The sample sections of the strip record reproduced in Fig. 10 show an even greater variation in luminescent activity with depth. At the shallowest level of 70 m, which was only

10 m deeper than the deepest level observed in the coastal water station, almost incessant but very irregular flashing occurred with both small and very large individual flashes. At 120 and at 180 m luminescent activity dropped to a few minor flashes with an occasional large one and contrasted very sharply with the conditions above and below these levels. The record of luminescence at 285 m shows intense activity with repeated flashes of moderate size and many large individual outbursts of light. The picture at 385 m is one of many fewer minor discharges with occasional very large flashes; at 410 m the large flashes are of about the same intensity, but there is a further reduction of the frequency and size of the smaller flashes.*

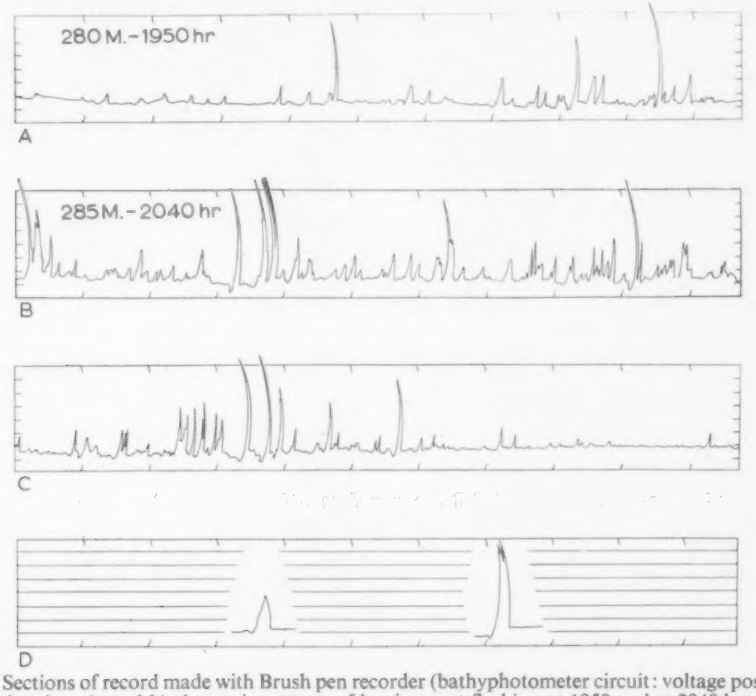

Fig. 11. Sections of record made with Brush pen recorder (bathyphotometer circuit: voltage position 9, scale 5) showing: (a and b) change in pattern of luminescent flashing at 1950 and at 2040 hours EST. at 280-285 m on 8 September, 1955; (c) change in luminescence while photometer was being raised at 2110 EST at a depth of about 130 m; and (d) two flashes from a 35-mm *Mnemiopsis leidyi* placed 50 cm from the receiving surface of the bathyphotometer in the Laboratory at Woods Hole on 14 September 1955.

Changes in time at the same level at this station were observed and samples of the record for periods beginning at 1950 and 2040 hours are shown in Fig. 11 (a and b). The pronounced differences may be due to a change in the behaviour of the animals or to a replacement of one set of animals by another either vertically or horizontally. We know that the vertical migration of certain animal groups takes place at earlier hours and probably other types of animals, undetected by the echo sounder, are changing level at these later hours. Variations in flashing might also be produced by the drift of the ship into or out of patches of animals. An example

* Following the preparation of this report records and quantitative measurements of luminescence were obtained in this general area during July 1956, at depths down to about 1,700 m and these will be fully presented in a subsequent report.

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of a pronounced change in the amount of luminescence during an actual observation was recorded at 2110 hours at a depth of about 130 m while the bathyphotometer was being reeled in at a rate of approximately 30 m/minute and the ship was drifting at about 60 m/minute (Fig. 11 c). Abrupt increase in flashing may result from the photometer moving either horizontally or vertically into a concentration of animals and in some instances luminescent discharge may be caused by the actual contact of animals with the photometer or its supporting cables. Conversely, abrupt decrease in flashing may be caused by the instrument moving away from the luminescent animals.

It was desired to obtain records with the Brush pen recorder of flashes of a known animal at a known distance from the photometer, although these cannot be compared quantitatively with the other records because of the characteristics of the circuits employed and the differences in the intensity of the background light, as explained above. Such records were obtained in the laboratory by placing the bathyphotometer in a light-tight box with the receiving surface of the instrument 50 cm from a glass dish containing sea water and a freshly caught 35-mm specimen of the ctenophore, *Mnemiopsis leidyi*. The ctenophore was caused to luminesce by applying a momentary charge of about 8 volts from a transformer to copper electrodes immersed in the water on each side of the animal (Fig. 11 d). Simultaneous reading of the microammeter in the bathyphotometer circuit showed that the intensity of light received at 50 cm was about 0·00005μw/cm^2 for the first flash shown and off scale at 0·000075μw/cm^2 for the second flash. The only previous measurement of the strength of luminescence of this type of animal known to us is that of NICHOLS (1924) in which the investigator using an optical pyrometer found the brightness of *Mnemiopsis leidyi* to be 0·116 to 0·30 millilambert. Although exact comparison of this value with ours is not possible because of the differences in the methods, rough calculation indicates that it is of the same order of magnitude.

Discussion. There is very little information on the vertical distribution of bioluminescence in the sea. The direct observations in the deep ocean by BEEBE (1934) from the bathysphere and by MONOD (1954) from the French bathyscaphe are of great interest but report little more than the presence of bioluminescence at all depths down to the greatest depths reached. MONOD found much less luminescence near the bottom at 1,400 m than at depths above this. BODEN and KAMPA (private communication) undertook similar observations with an underwater photometer off Hawaii and off southern California. They found that when the spectral sensitivity of the photometer was limited, differences in the vertical distribution of bioluminescence were recorded as a function of wavelength. They also reported that a correlation seemed to exist between the depth of luminescent activity and the position of a deep scattering layer during the evening migration of the latter.

The present observations show that at the coastal water station the luminescent activity is almost entirely restricted to the cold water beneath the thermocline (Fig. 9). The intensity of the flashes below the thermocline as observed on the microammeter makes it certain that flashes of like intensity would have been observed on the Brush pen recorder at the near-surface level, had they existed, in spite of the much higher background there due to surface illumination.

The maxima of luminescent activity shown for the slope water station (Fig. 10) are at 70 m and 285 m. The observation at 70 m probably represents luminescence

activity from euphotic zone inhabitants together with scattering layer animals which are at this and higher levels at the hour of the observation. The maximum at the 285 m level may be partly caused by the non-migrating members of the deep scattering layer (JOHNSON *et al.*, 1956) which is near this depth during daylight hours. The similarity of the records at 70 and 285 m does not indicate equal luminescent activity at these levels since that at 70 m is being displayed against a much higher background of light due not only to surface illumination but to the luminescent activity itself.

The commonest pelagic and bathypelagic sources of bioluminescence are probably found among the protozoans, ctenophores, euphausids, decapod crustaceans, cephalopods, salps, and fishes (HARVEY, 1952). Both intermittent luminescence and the steady condition of luminescence are found among the animals in these groups although the limited information available suggests that the former is the commoner condition. Of the types of animals mentioned we consider the protozoans, ctenophores, and salps the most likely sources at our coastal water station, whereas members of all of the first-mentioned groups might be important at the slope water station.

HARVEY (1952) summarizes what is known about the spectral distribution, intensity, periodicity, and other aspects of bioluminescence in animals. Certain more recent investigations are presented in the volume edited by JOHNSON (1955). However, aside from several fairly well-studied animals, such as the ostracod *Cypridina* and the firefly *Photinus*, precise quantitative information is scarce, particularly for oceanic forms. Thus it appears that we need not only to make further measurements of bioluminescence as a function of depth in the ocean but also to study the luminescent properties of representative individual species from the deep-sea fauna.

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The lignin fraction of marine sediments

RICHARD G. BADER

Abstract—The lignin in 31 surface samples of marine sediments from the Gulf of Maine and 26 samples from two cores collected in Puget Sound is an extremely variable fraction of their organic matter. In the two sediment cores, the loss of nonligninous carbon is about six times that of lignin carbon. Apparently lignin is extremely stable in the marine environment.

Lignin is important from a geological standpoint. Knowledge of its concentration in sediments may permit palaeoecologic interpretations which are not possible by use of total organic carbon alone. It is potentially useful as a tool in studies of rates of sedimentation; but it must be determined whether it is dependent or independent of the deposition of inorganic particles.

The possible effects of lignin on carbon-nitrogen relationships and the base-exchange capacity of the organic matter in marine sediments are also discussed.

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INTRODUCTION

LITTLE is known of the distribution of lignin in the marine environment. Its presence in marine sediments was first reported by TRASK (1932) and WAKSMAN (1933). BADER (1954) studied some surface concentrations of lignin in sediments from the Gulf of Maine.

Lignin is a very resistant organic complex, formed only by living plants (BERGENSTEIN, in BRAUNS, 1952) never by enzymatic or bacterial decay of other plant products. The decomposition of lignin is extremely slow (WAKSMAN and TENNY, 1926, 1927, 1929; BORUFF and BUSWELL, 1934; LEVINE *et al.*, 1935; BRAUNS, 1952, and others) and relatively constant under both aerobic and anaerobic conditions (ACHARYA, 1935, 1935a). In aerobic soils lignin is decomposed in traces or not at all (WAKSMAN and STEVENS, 1929, 1929a). It is the most resistant of all common plant materials. It is possible that in the microbiological decomposition of plant materials, lignin may act as an inhibitory factor (REGE, 1927; WAKSMAN and IYRE, 1932; FULLER and NORMAN, 1943) by the formation of stable lignoprotein complexes.

GOTTLIEB and HENDRICKS (1945) and others have attempted to isolate lignin from soils but were unable to secure definitely characterizable products. Methyl groups are apparently split off the lignin molecule (WAKSMAN and SMITH, 1934) and its cation exchange capacity increases (MILLER *et al.*, 1936). Despite the evidence for marked alteration, SCHOFFER and WELTE (1950) observed a striking similarity between the ultra-violet spectra of soil-lignin complexes and isolated lignin.

In the present investigation three general aspects were examined: (1) its distribution and variation in some marine sediments, (2) its stability in subsurface samples, and (3) its relationship to the remaining organic material.

METHOD OF ANALYSIS

Other organic compounds interfere with lignin determinations (WAKSMAN, 1933; NORMAN, 1937; BRAUNS, 1952) and must be removed. Lignin must then be determined indirectly because of its complexity and resistance to solution.

To remove the nonligninous organic matter, an extraction and hydrolysis series was used. From 50 to 100 grams of dried sediments were crushed, powdered, and then treated with acetone in a

Soxhlet extraction apparatus for 48 hours. The sediment was then removed from the Soxhlet and refluxed in 95 per cent ethyl alcohol for 24 hours. The solvent was changed three times during this period in order to increase the efficiency of extraction. This was followed by a transfer of the sample to a fritted disk filter. The sediment was then vacuum filtered and thoroughly washed with fresh, hot, ethyl alcohol. The sample was then dried, removed from the filter and the filter was washed with 4 per cent HCl. The first hydrolysis was then accomplished by refluxing the sediment in 4 per cent HCl. After 24 hours, the sample was vacuum filtered and washed thoroughly with distilled water, transferred to 72 per cent H_2SO_4 and kept at 8°C for three hours. This solution was then diluted to 4 per cent H_2SO_4 and refluxed for four hours. Following vacuum filteration and washing with distilled water the samples were dried, powdered, and thus made ready for the determination of lignin carbon. The residual organic material after the H_2SO_4 treatment is termed lignin; this includes its transformation products as well as nitrogenous compounds such as synthesized microbial lignoprotein complexes. The carbon from this source shall thus be called lignin carbon; the remaining carbon is termed nonligninous carbon and represents that carbon removed by previous treatment.

Table 1. *Surface sample data from are bounded by* 44°05′ *to* 44°28′*N and* 68° *to* 68°30′*W*

Sample No.	*Depth (ft.)*	*Total carbon (%)*	*Lignin carbon (%)*	*Nonligninous carbon (%)*	$\frac{\textit{Lignin carbon}}{\textit{Total carbon}} \times 100$
1	57	0·88	0·38	0·50	43·2
2	27	1·72	0·66	1·06	38·4
3	20	0·52	0·18	0·34	34·6
4	40	1·23	0·85	0·38	69·1
5	52	0·94	0·40	0·50	42·6
6	20	0·42	0·18	0·24	42·8
7	14	0·45	0·20	0·25	44·4
8	35	0·66	0·31	0·35	47·0
9	30	1·02	0·73	0·29	71·6
10	25	0·46	0·21	0·25	45·7
11	20	0·35	0·07	0·28	20·0
12	55	1·74	0·69	1·05	39·7
13	85	1·15	0·38	0·77	33·0
14	75	0·49	0·16	0·33	32·7
15	30	4·12	2·76	1·36	67·0
16	33	4·74	2·48	2·26	52·3
17	22	4·12	2·56	1·56	62·1
24	140	0·34	0·09	0·25	26·5
25	150	0·30	0·07	0·23	23·3
26	75	1·96	1·25	0·71	63·8
27	8	2·13	1·07	1·06	50·2
28	18	1·86	1·00	0·86	53·8
29	30	2·12	1·28	0·84	60·4
30	70	2·34	1·44	0·90	61·5
31	85	1·78	0·32	1·46	18·0
32	87	0·26	0·09	0·17	34·6
33	95	1·38	0·48	0·90	34·8
34	71	0·34	0·05	0·29	14·7
35	61	0·86	0·15	0·72	17·2
36	67	3·17	2·11	1·06	66·6
37	65	0·37	0·08	0·29	21·6
Mean			0·73	0·69	43·0
Standard deviation			0·25	0·15	16·8
Coefficient of variation			34·2	22·7	39·0

The total organic carbon and the lignin carbon were determined by a semimicro dry combustion method. The samples, dried to constant weight, were combusted in a measured volume of oxygen under controlled pressure. The evolved CO_2 was absorbed on Ascarite, determined gravimetrically and the per cent carbon computed. In determining the total organic carbon the sample was first

treated with warm, 4 per cent HCl to remove the carbonates. The use of such dilute HCl causes no loss of carbon from the organic matter. Carbon determinations by this method are reproducible to ± 0·03 per cent.

DISTRIBUTION AND RELATIVE STABILITY

The total organic carbon, lignin carbon, and the nonligninous carbon was determined for the 31 surface samples of marine sediments off the coast of Maine in the vicinity of Mt. Desert Island. These samples were collected by means of a "snapper" sampler and a gravity coring tube (see Table 1). The wide range and relatively large coefficient of variation of lignin carbon in total carbon indicates that lignin does not have a constant ratio to the other organic constituents.

Core No. 169 from Puget Sound (Table 2) is primarily composed of inorganic particles of a relatively uniform size in the silt range (0·062-0·004 mm). Between the depths of 15 and 43 cm in the core, the particle size grades from silt to fine sand (0·125 mm). From 43 to 65 cm the particle size grades back into the silt range. The

Table 2. Subsurface sample data

Sample No. and location	*Depth (cm)*	*Total carbon (%)*	*Lignin carbon (%)*	*Nonligninous carbon (%)*	$\frac{\text{Lignin carbon}}{\text{Total carbon}} \times 100$
169	0	1.02	0·66	0·36	64·7
(250 ft.)	6	0·94	0·64	0·30	68·1
	15	0·92	0·63	0·29	69·2
	30	0·37	–	–	–
	43	0·09	0·06	0·03	66·6
	55	0·36	–	–	–
47°21·5′N	65	0·79	0·64	0·15	81·0
123°08·2′W	85	0·76	0·62	0·14	81·6
	110	0·74	0·47	0·27	63·4
	115	0·74	0·69	0·05	93·2
	125	0·79	–	–	–
	134	0·78	–	–	–
	140	0·77	0·60	0·17	77·9
	148	0·85	0·64	0·21	75·3
221-C	0	1·96	1·16	0·80	59·2
(200 ft.)	7	1·63	1·08	0·55	66·3
	16	1·56	1·18	0·38	75·7
	32	1·93	1·11	0·82	57·6
	43	1·71	0·98	0·73	57·3
47°43·9′N	62	2·09	0·90	1·19	43·0
122°31·7′W	74	2·38	1·50	0·88	63·0
	97	1·97	1·02	0·95	51·8
	115	2·27	1·08	1·19	47·6
	125	1·78	1·49	0·29	83·7
	150	2·00	1·37	0·63	68·5
	155	1·98	1·16	0·82	58·5

total organic carbon correspondingly decreases in this sandy layer reaching a minimum value at 43 cm. The remaining variations in organic content are not associated with particle-size changes. The maximum concentration of total carbon and non-ligninous carbon occurs on the surface. With some minor variations, the per cent lignin carbon in the total carbon increases with depth.

Core No. 221-C from Puget Sound (Table 2) consists entirely of relatively uniform silt-sized particles. The fluctuations in organic content are not associated with

particle-size variations. The maximum concentration of total organic carbon is at 74 cm. For the immediate surface region, the per cent lignin carbon of the total carbon increases with depth, but below 16 cm this characteristic is not evident.

It appears that in the immediate surface sediments (0 to 6-7 cm) of both cores (Fig. 1) the lignin carbon decreases less rapidly with depth than the nonligninous carbon. Core No. 169 has a lignin carbon loss of 3·0 per cent and a nonligninous carbon loss of 16·6 per cent in the top 6 cm. Core 221-C has a 6·8 per cent lignin carbon loss and nonlignin carbon loss of 52·5 per cent in the top 7 cm. If it be assumed that environmental conditions have been relatively constant in both localities during this period of decomposition and that the organic decrease is due to decomposition, the percentage of nonligninous carbon loss is 5·5 to 7·7 times that of the lignin carbon. This indicates that the ligninous fraction is more resistant to decomposition than the greater part of the other organic compounds. These data (Table 2, Fig. 1) indicate that changes in the lignin carbon in excess of 1 per cent or 2 per cent per cm are due to supply changes, i.e., the lignin carbon loss due to decomposition is less than 1 per cent to 2 per cent of the total amount of lignin carbon.

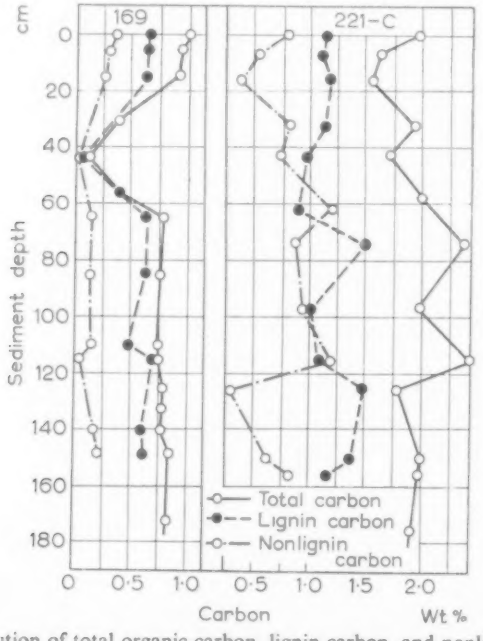

Fig. 1. Vertical distribution of total organic carbon, lignin carbon, and nonligninous carbon in two cores of Puget Sound sediments. The change in total, lignin, and nonlignin carbon in core 169 between 15 and 65 cm is a reflection of an inorganic particle size change, i.e. a sand layer. The remaining variations in core 169 and all of those in core 221-C are not related to particle size changes.

SOURCE OF ORGANIC MATTER

Although the greater part of the organic matter in marine sediments may be derived from the decomposition of planktonic organisms (SVERDRUP *et al.*, 1942) in regions of significant river drainage a considerable fraction may be derived from the land (GRIPENBERG, 1934). Since all analyses of ligninous material have been made

on samples obtained nearshore (Tables 1 and 2; TRASK, 1932; WAKSMAN, 1933), much, if not all, of this fraction too may have been derived from the land. Indeed, it has not yet been demonstrated that marine algae have lignin-like complexes similar to those of terrestrial algae (WAKSMAN, 1936). Hence, no definite conclusions can yet be made as to the actual source of the ligninous matter under consideration here.

SEDIMENTATION

The amount of organic matter included in marine sediments is related to the rate of inorganic sedimentation as well as to organic supply and decomposition. Variations in concentrations of organic matter can be explained by the following means:

(1) A high rate of sedimentation of inorganic material would result in diluting the simultaneously deposited organic matter and *vice versa.*

(2) A low rate of sedimentation would increase the time that the organic fraction remains in the upper oxidizing zone of the sediments. It would thus have a longer period of active decomposition.

(3) A decrease in the supply of organic material would cause a corresponding decrease in the sediments, and *vice versa.*

(4) Environmental changes not effecting the supply or rate of sedimentation of organic material may alter the rate of microbiological decomposition.

The data from Core 221-C (Fig. 1) shows a decrease in total organic carbon from 74 to 43 cm. This could be explained on the basis of any of the four mechanisms listed above. One might conclude that this segment existed in an environmental situation that changed continually and gradually with time. However, the lignin carbon concentration decreases appreciably from 74 to 62 cm, as the nonligninous carbon increases. From 62 to 43 cm the lignin carbon increases slightly although the nonlignin carbon decreases markedly. Similar situations occur between 97 and 74 cm and 150 to 155 cm. These observations of the ligninous portion indicate that there was not a constantly and gradually changing environment over these depth ranges; other factors must be involved.

CARBON-NITROGEN RATIO

The wide variation in the lignin content of marine sediments and its resistance to decomposition may explain the wide variations in carbon-nitrogen ratios in marine sediments (GRIPENBERG, 1934; MOHAMED, 1949; ARRHENIUS, 1950; BADER, 1955). Since lignin may inhibit organic decomposition and may be associated with the microbiological formation of stable lignoprotein complexes (REGE, 1927; WAKSMAN and IYER, 1932; FULLER and NORMAN, 1943), sediments with a high lignin content have the potentiality of " trapping " more nitrogen per unit of organic material than sediments with low lignin concentrations, since nitrogen associated with lignin would be less mobile than that in the remaining organic compounds.

BASE-EXCHANGE CAPACITY

Discussions of base exchange in marine sediments have been confined to the clay-water system (KELLY, 1955) and little is known of the effect of organic material in this connection.

The organic fraction of soils has approximately seven to eight times the exchange capacity of the mineral fraction (TURNER, 1932; GEDROIZ, 1933). The base exchange

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capacity of soil organic matter accounts for as much as 61 per cent of the total capacity (MITCHELL, 1932; WILLIAMS, 1932). In a podsol soil 87 per cent of the exchange capacity was due to the organic constituents (BARSHAD and ROJAS-CRUZ, 1950). In a soil containing 4 per cent organic matter, well within the range found in continental-shelf sediments, 40 per cent of the total exchange capacity has been attributed to this organic fraction. Ligninous complexes are capable of irreversibly adsorbing NH_3 and other bases (WEDEKIND and GARRE, 1928).

Although free lignin has a very low exchange capacity, when it is combined with protein to form a complex, the increase in base exchange capacity far exceeds the sum of the two and closely approximates the exchange capacity of the total humus (WAKSMAN and IYER, 1932). These data indicate that the lignoprotein fraction may be responsible for much of the base-exchange capacity in the organic matter of marine sediments. The contribution to the total exchange capacity by the organic matter in the sediments should vary markedly according to the amount of lignin complexes present. Hence, organic matter in general and lignin in particular may be important factors in the early diagenetic processes in marine sediments.

SUMMARY

(1) The total lignin content and its ratio to the total organic material in marine sediments is extremely variable.

(2) Lignin is an organic complex displaying extreme resistance to microbiological decomposition. The loss of nonligninous carbon is approximately six times greater than the lignin carbon loss. Lignin carbon changes which exceed 1 per cent to 2 per cent per cm of the total may thus be ascribed to changes in the amount originally supplied to the sediments.

(3) Concentration of carbon from ligninous sources in marine sediments should give further information for palaeoecology.

(4) The concentration of lignin in marine sediments may be associated with variations in carbon-nitrogen ratios, due to its variability, stability, and the formation of nitrogen-bearing lignin complexes.

(5) When investigating the physicochemical system in marine sediments the effect of lignin and lignin complexes on this system should be considered, since studies of soils indicate that this fraction accounts for most of the base-exchange capacity attributed to organic materials.

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Contribution No. 200 *from Department of Oceanography, University of Washington, Seattle, Washington. Author's present address: Department of Oceanography, A. & M. College of Texas, College Station, Texas.*

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A β-plane analysis of free periods of the second class in meridional and zonal oceans

A. B. ARONS and HENRY STOMMEL

Abstract—Quasigeostrophic free oscillations (or barotropic seiches) of meridional and zonal oceans are analysed for plane oceans of uniform depth and nonuniform rotation (the approximation of the β plane). These motions have been denoted " motions of the second class " by tidal theorists. An attempt is made to clarify the physical nature of such oscillations and to calculate periods and wavelengths which give an idea of the orders of magnitude which are involved.

INTRODUCTION

TIDAL theorists have long recognized* that rotation of a globe covered with a thin fluid layer of uniform depth and density not only introduces changes in the frequencies of free long-wave standing oscillations which exist on the globe even in the absence of rotation (so-called oscillations of the first class), but also converts certain motions which are steady in the absence of rotation into long-period oscillations (so-called oscillations of the second class). In the terrestrial atmosphere and oceans, waves of the first class are usually spoken of as tidal waves. On the other hand, waves of the second class are nearly in geostrophic balance, and therefore appear as moving wind systems for example, planetary waves (ROSSBY, 1939), or moving current systems in the ocean. The ordinary method of oceanographic-current determination – dynamic computation – reveals only internal modes of second class motions. The external mode of second class motion in the ocean must appear as a relatively long-period oscillation of the free surface, and as we will show in this paper is quite possibly excited by atmospheric storms. A study of observations has not been made. In the spherical system, the introduction of meridional walls or coasts makes the mathematics rather difficult, although GOLDSBROUGH (1933) has been able to obtain approximations for the free periods in an ocean of uniform depth (12,880 ft) bounded by meridians 60° apart (to approximate the Atlantic) including the second-class period (7·1 sidereal days). However, there are a number of physical questions that remain somewhat obscure. For example, planetary waves all have westwardly directed phase velocity, and in compounding free second-class waves to produce a standing wave between two walls, we do not have any waves that move toward the east. In what sense, then, can a second-class wave (or planetary wave) reflect from a meridional barrier ? In order to clarify some of these questions we have transferred the problem to the dynamical system of the beta plane : that is, instead of treating the rotating globe, we study the dynamics of waves on a plane ocean of uniform depth with nonuniform rotation. Our results are therefore not exact, but they are more easily manipulated, and we feel that certain physical features of second-class waves undergoing reflection at a barrier, and of the eigenvalue problem of standing waves between two barriers, emerge more clearly than from the more exact but more complicated dynamical system. In fact, that is our only excuse for dealing with the inexact beta

* For example see LAMB's (1932, p. 350 ff) discussion of HOUGH's tidal studies.

plane, rather than the exact rotating sphere. A brief derivation of the fundamental equations involved is given in the Appendix.

PROPERTIES OF PLANETARY WAVES

A brief derivation of the fundamental equation describing the propagation of plane planetary waves in the x (east-west) direction in an ocean of uniform depth D_0 is given in the Appendix. This equation has the form:

$$\lambda^2 \frac{\partial^3 \eta}{\delta t \, \partial x^2} - \frac{\partial \eta}{\partial t} + \beta \lambda^2 \frac{\partial \eta}{\partial x} = 0 \tag{1}$$

where η is the displacement of the free surface from its unperturbed level. Also:

$$\beta \equiv \partial f / \partial y,$$

where f is the Coriolis parameter $2\Omega \sin \phi$, and

$$\lambda^2 \equiv g D_0 / f^2$$

λ is ROSSBY's " radius of deformation."

Consider plane-wave solutions of the form:

$$\eta = A e^{i(\omega t - kx)} \tag{2}$$

representing wave trains of angular frequency ω and wave number k propagating in the positive x (easterly) direction.

Substitution of equation (2) into equation (1) gives the characteristic equation:

$$\omega = \frac{-\beta k \lambda^2}{1 + k^2 \lambda^2}. \tag{3}$$

The negative sign in equation (3) has to do with the direction of the phase velocity of the wave train. If we denote phase velocity by c, we have:

$$c = \frac{\omega}{k} = \frac{-\beta \lambda^2}{1 + k^2 \lambda^2}. \tag{4}$$

Thus the phase velocity is inherently negative, i.e. always in the westerly direction, as originally demonstrated by ROSSBY.

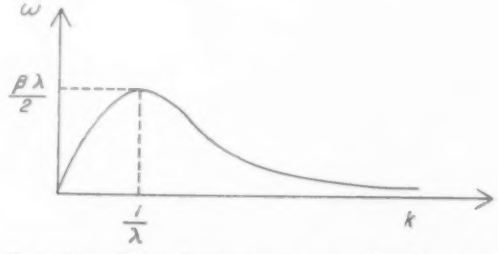

Fig. 1. Sketch of the dispersion relation for planetary waves (equation 3) without regard for the negative sign.

In a dispersive wave system such as that being dealt with in this analysis, energy is propagated at the *group* rather than the *phase* velocity. Denoting the group velocity

by U, we have

$$U = \frac{d\omega}{dk} = \beta\lambda^2 \left[\frac{k^2\lambda^2 - 1}{(k^2\lambda^2 + 1)^2}\right] \tag{5}$$

by differentiation of equation (3).

The functional relationship between ω and k (without regard to the algebraic sign of equation (3) is sketched in Fig. 1.

Equation (5) shows that ω has a maximum at $k = 1/\lambda$. At this wave number, ω has the value $\beta\lambda/2$, and U is equal to zero. Then from equation (5):

(a) For $k < 1/\lambda$, $U < 0$; group velocity westward,

(b) For $k > 1/\lambda$, $U > 0$; group velocity eastward. (6)

Restating conditions (6) verbally: For wavelengths greater than $2\pi\lambda$, energy will always be propagated in the westward direction; while for wavelengths shorter than $2\pi\lambda$, energy will always be propagated in the eastward direction despite the westwardly directed phase velocity.

The waves being described have pressure gradients in the east-west direction, very small particle velocity (u) in this direction, and substantial particle velocities (v) in the north-south direction.

These physical properties of planetary waves suggest examination of the free oscillations (standing waves) of an ocean bounded by meridional walls in simple terms of incident and reflected wave trains superposed to satisfy the boundary conditions:

$$u = 0 \text{ at } x = 0 \text{ and at } x = L \tag{7}$$

where L is the width of the meridional ocean.

STANDING PLANETARY WAVES IN A MERIDIONAL OCEAN

From equation (A15) in the Appendix and condition (7) above, we have the requirement that:

$$\frac{\partial^2 \eta}{\partial t\, \partial x} = 0 \qquad \text{at} \qquad x = 0 \qquad \text{and} \qquad x = L \tag{8}$$

Consider the superposition of two westwardly propagating wave trains:

$$\eta = A_1 e^{i(\omega_1 t + k_1 x)} + A_2 e^{i(\omega_2 t + k_2 x)} \tag{9}$$

Equation (8) requires that:

$$-A_1 \omega_1 k_1 e^{i(\omega_1 t + k_1 x)} - A_2 \omega_2 k_2 e^{i(\omega_2 t + k_2 x)} = 0 \quad \text{at} \quad x = 0 \quad \text{and} \quad x = L \tag{10}$$

To satisfy equation (10) at $x = 0$ for all values of t we have the requirements that:

$$\omega_1 = \omega_2 = \omega$$

$$A_1 k_1 = -A_2 k_2$$

We then have the requirement at $x = L$

$$A_1 k_1 \left[e^{i(\omega t + k_1 L)} - e^{i(\omega t + k_2 L)}\right] = 0 \tag{11}$$

Equation (11) is satisfied for all values of t if:

$$k_{2n} L = k_{1n} L + n(2\pi) \tag{12}$$

where $n = 0, 1, 2, 3, \ldots\ldots$

The case $n = 0$ represents a trivial or degenerate solution in which two wave trains of the same ω and k but of opposite phase cancel each other. The other cases represent possible planetary modes of the meridional ocean.

EVALUATION OF PERIODS OF THE ALLOWABLE MODES

Because of the double-valued nature of the dispersion relation (equation 3), it is possible to find two values of k corresponding to the same ω and simultaneously satisfying equation (12).

If we drop the negative sign in equation (3) and solve for the roots of the equation, setting the smaller root equal to k_1, we obtain:

$$\begin{aligned} k_1 &= \frac{\omega_0}{\omega\lambda}\left\{1 - \left[1 - \left(\frac{\omega}{\omega_0}\right)^2\right]^{\frac{1}{2}}\right\} \\ k_2 &= \frac{\omega_0}{\omega\lambda}\left\{1 + \left[1 - \left(\frac{\omega}{\omega_0}\right)^2\right]^{\frac{1}{2}}\right\} \end{aligned} \tag{13}$$

where

$$\omega_0 \equiv \beta\lambda/2$$

Imposing on equations (13) the simultaneous restriction of equation (12), we obtain the periods of the allowable modes:

$$\frac{\omega_0}{\omega_n} = \frac{T_n}{T_0} = \left(1 + n^2 \frac{\pi^2 \lambda^2}{L^2}\right)^{\frac{1}{2}} \tag{14}$$

or, alternatively, in terms of primary parameters:

$$T_n = \frac{4\pi f}{\beta (g D_0)^{\frac{1}{2}}}\left[1 + n^2 \frac{\pi^2 g D_0}{L^2 f^2}\right]^{\frac{1}{2}} \tag{15}$$

Thus the mode or standing wave pattern is set up by the superposition of two wave trains of westward phase velocity and different wave number. Since the wave numbers lie on opposite sides of the maximum in Fig. 1, one train (that of lower wave number and longer wavelength) is associated with a westward *group* velocity and propagation of energy, while the wave train of higher wave number and lower wavelength is associated with an *eastward* propagation of energy. One wave train may be considered an incident wave, and the other train is then the reflection which occurs at the meridional boundaries.

The wavelengths corresponding to the two trains making up a mode of oscillation are given by:

$$\Lambda_{1n} = \frac{2\pi\lambda}{\frac{T_n}{T_0} - n\frac{\pi\lambda}{L}} \tag{16}$$

$$\Lambda_{2n} = \frac{2\pi\lambda}{\frac{T_n}{T_0} + n\frac{\pi\lambda}{L}} \tag{17}$$

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where Λ_{1n} and Λ_{2n} are the wavelengths associated with the wave numbers k_{1n} and k_{2n} respectively.

ROSSBY (1939) gives a convenient table of values for f and β for use in computations of this kind. A sample set of computed results for the first mode ($n = 1$) is given in Table 1, illustrating the orders of magnitude of period and wavelength and the effects of such parameters as latitude ϕ, ocean depth D_0, and ocean width L. A plot of the period results is shown in Fig. 2.

Table 1. *Periods and wavelengths associated with first mode of standing planetary waves in an ocean with meridional boundaries.*

Ocean width $L\times10^{-3}$ km	*Ocean depth* D_0 km	*Latitude* $\phi = 30°$			*Latitude* $\phi = 45°$			*Latitude* $\phi = 60°$		
		T_1 *days*	$\Lambda_1\times10^{-3}$ *km*	$\Lambda_2\times10^{-3}$ *km*	T_1 *days*	$\Lambda_1\times10^{-3}$ *km*	$\Lambda_2\times10^{-3}$ *km*	T_1 *days*	$\Lambda_1\times10^{-3}$ *km*	$\Lambda_2\times10^{-3}$ *km*
2	2	12·2	75·2	1.95	15·6	38·4	1·90	22·9	26·2	1·86
4		6·92	40·2	3·65	9·63	21·7	3·39	15·1	15·4	3·18
6		5·42	29·4	4·98	8·08	16·6	4·42	13·2	12·2	4·02
8		4·78	24·4	6·02	7·47	14·3	5·13	12·4	10·7	4·57
12		4·27	19·6	7·45	7·00	12·1	6·03	11·9	9·32	5·25
18		4·02	16·9	8·70	6·77	10·8	6·78	11·6	8·50	5·78
2	4	11·9	147	1·98	14·9	75·2	1·95	21·5	49·4	1·92
4		6·36	77·0	3·81	8·44	40·2	3·65	12·8	27·9	3·49
6		4·70	53·7	5·40	6·61	29·4	4·98	10·45	20·9	4·66
8		3·95	43·3	6·76	5·83	24·4	6·02	9·48	17·7	5·52
12		3·32	33·1	8·82	5·22	19·6	7·45	8·73	14·7	6·61
18		2·99	27·1	10·8	4·91	16·9	8·70	8·36	13·0	7·53
2	6	11·7	222	2·00	14·6	112	1·96	21·0	75·2	1·95
4		6·16	113	3·86	8·02	58·5	3·74	11·9	40·2	3·65
6		4·42	78·6	5·58	6·06	41·8	5·23	9·36	29·4	4·98
8		3·53	70·2	7·18	5·20	33·9	6·47	8·26	24·4	6·02
12		2·92	46·0	9·50	4·48	26·5	8·27	7·40	19·6	7·45
18		2·54	36·4	12·0	4·12	22·1	9·87	6·95	16·9	8·70

In Table 1 it will be noted that the wavelength associated with the Λ_1 component is generally substantially greater than the ocean width L. This leads one to speculate about a physical situation in which the shorter Λ_2 component might be excited by essentially random meteorological processes, etc. with reflections at the boundaries introducing Λ_1. The ocean level would then rise and fall with period T_1, in some cases with very little phase difference between the opposite boundaries. (In the β plane model of infinite north-south canal, the apparent continuity paradox is resolved by the divergence of the north-south flow.)

Table 2. *Periods of first and second modes for various specific cases.*

Ocean	*North Atlantic*		*South Atlantic*	*North Pacific*		*South Pacific*	*Indian*
Latitude	30°	45°	30°	30°	45°	30°	30°
Avg. $L\times10^{-3}$ km	5·8	3·5	5·8	11·5	6·7	9·6	7·8
Avg. D_0 km	4·5	3·5	4·0	5·5	5·0	4·5	4·0
T_1 (days)	4·7	9·6	4·8	3·0	6·0	3·5	4·0
T_2 (days)	8·2	16·6	8·3	4·6	9·5	5·3	6·6

Table 2 shows a number of periods (T_1 and T_2) computed for specific oceanic conditions, with rough average values of L and D_0 estimated from the charts.

In the case of the North Atlantic, the values of T_1 (4·7 and 9·6 days at 30° and 45° respectively) straddle GOLDSBROUGH's (1933) value of 7·1 days for the fundamental

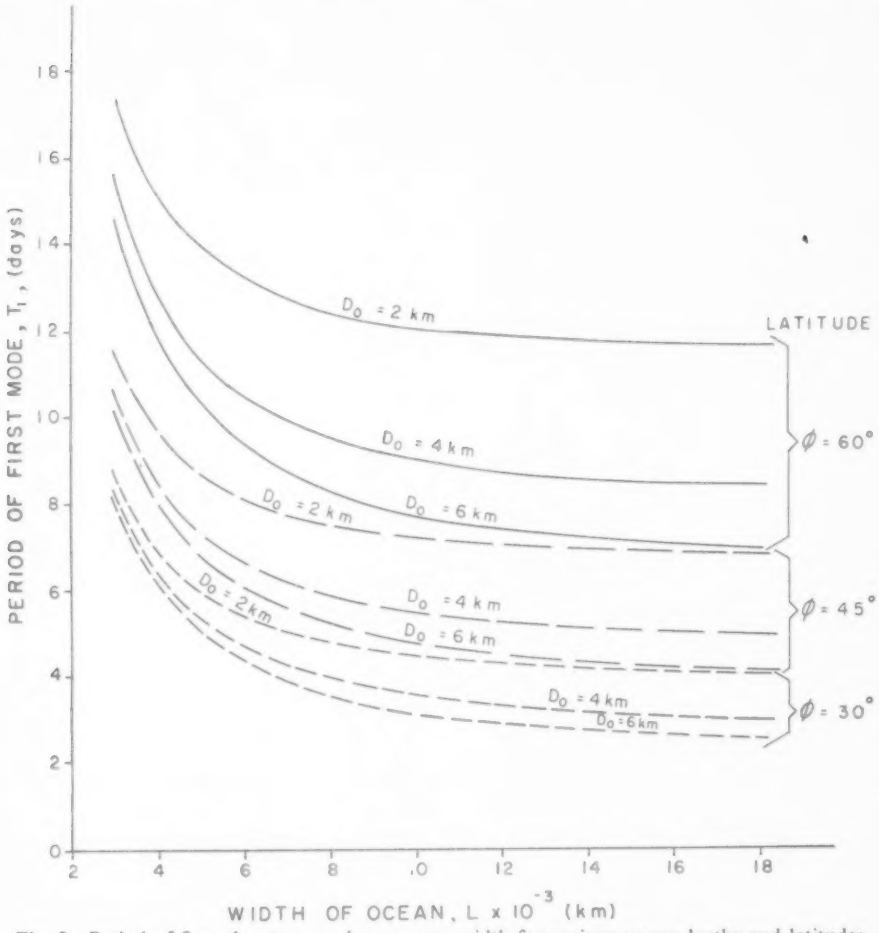

Fig. 2. Period of first planetary mode vs. ocean width for various ocean depths and latitudes.

spherical mode cited in the Introduction above. Thus one might expect to observe long wave motions in the North Atlantic, with associated north-south particle velocities, having periods in the range indicated. Similarly one might expect to observe periods of about 4 or 5 days in the North Pacific.

FREE PERIODS OF A ZONAL OCEAN

In the case of a zonal ocean (such as the Antarctic Circumpolar), standing waves must divide the ocean length or circumference into an integral number of wavelengths, giving the condition:

$$L = n\,\Lambda_n = n\,\frac{2\pi}{k_n} \tag{18}$$

where $n = 1, 2, 3, \ldots\ldots$

Substitution of equation (18) into equation (3), dropping the negative sign of the latter, gives:

$$\frac{T_n}{T_0} = \frac{\omega_0}{\omega_n} = \frac{\tau_n}{2}\left(1 + \frac{1}{\tau_n^2}\right) \tag{19}$$

where

$$\tau_n \equiv n\,(2\pi\lambda/L)$$

or, in terms of primary parameters:

$$T_n = \frac{4\pi^2\,n}{\beta L}\left[1 + \frac{L^2\,f^2}{4\pi^2\,n^2\,g\,D_0}\right] \tag{20}$$

Modes calculated for the Antarctic Ocean are given in Table 3.

Table 3. Free periods for the Antarctic Ocean. Assumed parameters: $\phi = 55°$; $L = 25{,}000$ km; $D_0 = 4{\cdot}0$ km.

n	T_n (*days*)	$\Lambda_n \times 10^{-3}$ (*km*)
1	9·33	25·0
2	6·75	12·5
3	6·82	8·33
4	7·53	6·25
5	8·53	5·00
6	9·68	4·17
7	10·9	3·57
8	12·1	3·13
9	13·4	2·78
10	14·7	2·50

The results of Table 3 show an interesting clustering of periods in the neighbourhood of the maximum of the dispersion curve (Fig. 1). For this case, the wavelength associated with the dispersion maximum ($k = 1/\lambda$) is 10,500 km. The first two periods have smaller wave number (larger wavelength) and fall at positions to the left of the maximum in Fig. 1. The higher modes all have wave numbers to the right of the maximum. This relation among the parameters accounts for the initial decrease and subsequent increase in the periods and for their clustering – which takes place in the neighbourhood of the dispersion maximum. The calculations imply that there might be a fairly strong weekly period in the surface levels and north-south particle velocities of the Antarctic Ocean.

SUMMARY

Although this treatment of second-class motions on the β plane is obviously unsophisticated, we feel that it clarifies the physical nature of the model being invoked and of the phenomena taking place, thus deepening our insight into the meaning of the more abstract results obtained by the tidal theorists. It seems quite possible that motions of this type might be excited by meteorological as well as tidal forces and that the motions thus induced in the ocean depths might play a significant role in affecting the history of the oceanic water masses.

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APPENDIX

The equation for planetary waves in an ocean of uniform depth.

Given the hydrodynamic equations of motion in a right-handed co-ordinate system with x directed to the east, y to the north, and z upward:

$$\frac{Du}{Dt} - fv + (2\Omega \cos\phi)\, w = -\frac{1}{\rho}\frac{\partial p}{\partial x} \tag{A1}$$

$$\frac{Dv}{Dt} + fu = -\frac{1}{\rho}\frac{\partial p}{\partial y} \tag{A2}$$

$$\frac{Dw}{Dt} - (2\Omega \cos\phi)\, u = -\frac{1}{\rho}\frac{\partial p}{\partial t} - g \tag{A3}$$

where $f \equiv 2\Omega \sin\phi$, and u, v, w are the x, y, z components of velocity respectively. ϕ is the angle of latitude, Ω the angular velocity of the earth, ρ the density, p the pressure.

Dropping inertial terms and assuming hydrostatic equilibrium in the vertical direction, we have:

$$\frac{\partial u}{\partial t} - fv = -\frac{1}{\rho}\frac{\partial p}{\partial x} \tag{A4}$$

$$\frac{\partial v}{\partial t} + fu = -\frac{1}{\rho}\frac{\partial p}{\partial y} \tag{A5}$$

$$0 = -\frac{1}{\rho}\frac{\partial p}{\partial z} - g \tag{A6}$$

where ρ will be taken as constant through the body of the fluid and u and v constant with depth.

Consider a body of fluid with a free surface and a uniform unperturbed depth D_0. If η denotes displacements of the surface from the unperturbed level, equations (A4) and (A5) take the following form after making use of equation (A6):

$$\frac{\partial u}{\partial t} - fv = -g\frac{\partial \eta}{\partial x} \tag{A7}$$

$$\frac{\partial v}{\partial t} + fu = -g\frac{\partial \eta}{\partial y} \tag{A8}$$

The equation of continuity for this case takes the form:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = -\frac{1}{D_0}\frac{\partial \eta}{\partial t} \tag{A9}$$

Cross differentiating equations (A7) and (A8) with respect to y and x respectively, and subtracting to eliminate the second derivatives of η, we obtain:

$$\frac{\partial^2 v}{\partial x\, \partial t} - \frac{\partial^2 u}{\partial y\, \partial t} + f\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right) + \beta v = 0 \tag{A10}$$

where

$$\beta \equiv \partial f / \partial y$$

We now make a quasigeostrophic approximation by setting

$$v \simeq \frac{g}{f}\frac{\partial \eta}{\partial x}; \qquad u \simeq \frac{g}{f}\frac{\partial \eta}{\partial y} \tag{A11}$$

in the first, second, and fourth terms of equation (A10), and utilize the continuity equation (A9) to make a substitution for the third term. The resulting equation in η is:

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$$\frac{g}{f}\frac{\partial^3 \eta}{\partial t\,\partial x^2} + \frac{g}{f}\frac{\partial^3 \eta}{\partial t\,\partial y^2} + \frac{g\beta}{f^2}\frac{\partial^2 \eta}{\partial t\,\partial y} - \frac{f}{D_0}\frac{\partial \eta}{\partial t} + \frac{g\beta}{f}\frac{\partial \eta}{\partial x} = 0. \tag{A12}$$

We shall concern ourselves with the propagation of plane waves in the x direction and therefore drop the second and third terms, leaving the fundamental equation:

$$\lambda^2 \frac{\partial^3 \eta}{\partial t\,\partial x^2} - \frac{\partial \eta}{dt} + \beta\lambda^2 \frac{\partial \eta}{\partial x} = 0 \tag{A13}$$

where

$$\lambda^2 \equiv g\,D_0/f^2 \tag{A14}$$

Equation (A13) is an equation for free oscillations of a medium subject to the restrictions and quasigeostrophic approximation used above. It describes planetary waves identical with those originally identified by ROSSBY (1939) in a somewhat more complicated context.

For the case of plane waves propagating in the x direction, equations (A8) and (A11) yield the following expression for the particle velocity u:

$$u = -\frac{g}{f^2}\frac{\partial^2 \eta}{\partial t\,\partial x} \tag{A15}$$

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Some properties of sea water influencing the formation of Antarctic bottom water

N. P. FOFONOFF

Abstract—The formation of Antarctic bottom water appears to be influenced and controlled by nonlinearities in the dependence of density of sea water on temperature and salinity. Properties of the bottom water are shown to be determined primarily by the temperatures and salinity of the warm deep water, hence seasonal variations of the temperature and salinity of the bottom water are suppressed.

INTRODUCTION

KNUDSEN (1901) and EKMAN (1908) gave a set of empirical formulae expressing the density of sea water as a function of temperature, salinity, and pressure. The accurate relationships expressing the equation of state of sea water are not required in many practical and theoretical problems and it is usually sufficient to regard the density of sea water as being constant or as varying in a simple way with temperature, salinity and pressure. In some problems the more exact relationships must be considered. The study of the mixing of sea water is an example. Nonlinearities in the equation of state are important in determining certain characteristics of ocean structure that are influenced by mixing, particularly the formation of distinct water types in the ocean. A familiar and closely related example is the temperature distribution of the deep water in lakes which is determined primarily by the physical properties of water rather than the energy exchanges across the surface of the lake.

A small decrease in volume occurs when two water types of different temperatures and salinities are mixed together at constant pressure. The contraction is easily demonstrated with the help of density tables. Examples are given by SVERDRUP *et al.* (1942, p. 415-416). The opposite effect, a slight expansion of the mixture, can occur in vertical mixing where the water types are at different pressures. The volume changes are very small ($\sim 10^{-5}$ cm^3/gm) but significant in considering the buoyancy of the mixture and the changes of potential energy brought about by mixing.

WITTE (1902) was the first to point out that because of the contraction the mixing of two dissimilar types of sea water of nearly equal density would yield a mixture that is more dense than either type. He argued that a sharp boundary could be set up and maintained between cold, less saline, and warm, more saline, water by the continual sinking of the heavier mixture. However, the effectiveness of this process is doubtful and no quantitative demonstrations of it have been given.

The formation of a mixture that is more dense than its components is best seen with the aid of a $T - S$ diagram on which isopycnals (constant sigma $= t$) are drawn, as in Fig. 1. Homogeneous water types are represented by points and the locus of the mixtures of any two types by a straight line joining the two points.* Mixtures of highest density occur at the point where the line of mixtures is tangent

*The locus of mixtures of two water types is curved slightly in the opposite sense to that of the isopycnals because of the variation of the specific heat of sea water. Departures from the straight line are negligible.

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to an isopycnal. If no tangent occurs, one of the water types is more dense than any mixture it can form with the other.

The formation of Antarctic bottom water provides an interesting example of how nonlinearities in the properties of sea water influence, and to a considerable extent determine, the resultant structure of the bottom water.

FORMATION OF ANTARCTIC BOTTOM WATER

Antarctic bottom water is formed principally in the south-west part of the Weddell Sea (DEACON, 1937, p. 109) and consists of a mixture of warm deep water and water from the continental shelf (MOSBY, 1934, p. 84).

MOSBY (1934) pointed out that shelf water at freezing temperature (approx. — 1·9°C) required a salinity of at least 34·62‰ to form, by mixing with the warm deep water, bottom water having the observed characteristics.

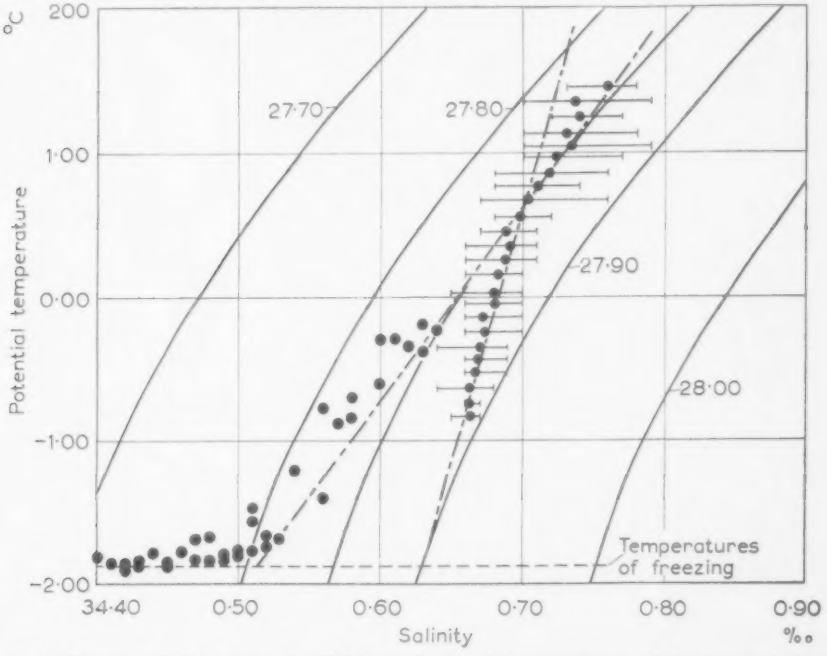

Fig. 1. A diagram relating averaged salinities and potential temperatures of the Antarctic bottom water (points with bars) and showing the minimum observed temperatures of the surface layers (points without bars) in the Weddell Sea region.
The horizontal bars show the maximum range of salinities in each one-tenth degree interval of potential temperature. The two broken lines indicate tangents to curves of constant sigma – t at — 1·89°C, 34·63‰, and 0·60°C, 34·70‰.

Data for the present paper were selected from oceanographic stations occupied by *Discovery II*, *Deutschland* and *Norvegia* in the Weddell Sea and the adjacent regions. About 140 stations were examined, the majority being those of *Discovery II*. The data show that the salinity of the shelf water (assumed to be at freezing temperature) which mixes to form bottom water is confined to a narrow salinity range centred at 34·63‰. The data were summarized by averaging the salinities from a number of

stations in each one-tenth degree interval of potential temperature θ, and the averages plotted in Fig. 1. The horizontal bars show the maximum range of salinities in each interval, the spread arising partly from horizontal gradients and partly from errors inherent in the salinity determinations; for example, the *Deutschland* stations show lower salinities on the average than those of *Discovery II*. Salinities were included up to the level of the salinity maximum only and the averages consist of from 7 to 50 observations in each temperature interval. Warm deep water is only partly represented in the diagram as most of it lies above the salinity maximum.

A break in the mean $\theta - S$ curve occurs at approximately-0·6°C, the curve rising less steeply for the warmer waters north of the Weddell Sea. For this reason, the point (0·6°C, 34·70‰) is considered as the lower limit of temperature of the warm deep water, and colder water as belonging to either surface or bottom water types.

It is remarkable that to within the accuracy to be expected of salinity determinations the $\theta - S$ curve for the bottom water forms a straight line which, if extended, is tangent to an isopycnal at approximately the freezing point of sea water. An actual tangent at $-1{\cdot}89$°C, 34·63‰, is shown by a broken line. The tangency of the $\theta - S$ curve to an isopycnal at freezing temperature represents the critical condition at which shelf water is more dense than any mixture it can form with the warm deep water. It defines the lower limit of salinity at which the shelf water must mix and flow down the continental slope. Shelf water of higher salinity cannot accumulate on the shelf in large quantities except in basins cut off from the open sea by submarine ridges.

Because of the contraction on mixing, shelf water in the salinity range 34·51‰ to 34·63‰ forms some mixtures with the warm deep water which are more dense than either type. Shelf water in this salinity range cannot float freely over the warm deep water and is also prevented from sinking by its heavier mixtures. It is, therefore, found only on the continental shelf and has not been observed in the open sea.

At a salinity of 34·51‰ a second critical condition is reached (indicated in Fig. 1 by a tangent at 0·6°C and 34·70‰), at which the shelf water together with all its mixtures is less dense than the warm deep water of the Weddell Sea. Shelf water of lower salinity can float freely over the warm deep water and is found to be widely distributed in the surface layers. The lowest observed temperatures of the surface layer are shown in Fig. 1 by the points without bars. Surface water at freezing temperature, presumably flowing without mixing from the shelf, has been observed in the open sea with salinities up to 34·51‰. At higher salinities the coldest water is found to be a mixture of warm deep water with shelf water of salinity 34·51‰.

The bottom water appears to be formed primarily in the Weddell Sea. In no other region, excepting the Ross Sea (DEACON, 1939) is the surface water observed to have sufficiently high salinity to enable it to penetrate the warm deep water.

CONCLUSIONS

The structure of the Antarctic water appears to be determined to a large extent by the nonlinearities in the equation of state for sea water. The $T - S$ curve for the bottom water is found to depend primarily on the temperature and salinity of the warm deep water rather than the shelf water; thus seasonal variations in the properties of the bottom water are suppressed.

The mechanism by which shelf water is selected in the formation of bottom water

operates critically only at low pressure. As unmixed shelf water has not been observed at great depths, it follows that bottom water is formed principally in shallow water, and further mixing at greater depths does not appreciably alter its $\theta - S$ relationship.

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National Institute of Oceanography, Wormley, England.

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Interpretation of high-resolution echo-sounding techniques and their use in bathymetry, marine geophysics, and biology

S. T. KNOTT and J. B. HERSEY

Abstract—Experience in making observations with commercially available correlation recorders designed for sounding ocean depths has suggested design modifications which would combine the capabilities of both shallow- and deep-water sounders in one instrument as well as improve their general performance for research. The design and construction of such a recorder is described. Some examples are given of its application to the study of smaller-scale bottom features ; to the echolocation of fish schools, individual fishes, and other aggregations of marine animals ; and for locating instruments in depth and range.

Occasionally echo-sounder pings penetrate the bottom to reflect from deeper horizons ; the recorder then presents a continuous-structure section. By using a sound source having a broad spectrum instead of the usual single-frequency ping, and by extending the receiver design to record in two or more filter bands, shallow structures have been observed which could not be recorded with the high frequency of the conventional echo sounder.

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INTRODUCTION

FOR many years the acoustic signals from an echo sounder have been recorded in such a way that the echoes from one sound pulse can conveniently be correlated with those of neighbouring pulses by the familiar device of moving a recording stylus across the short dimension of a long strip of recording paper, the latter moving along its length under the stylus carriage. The time of the outgoing sound pulse is controlled by the position of the stylus and is usually made to occur when the stylus has just started its traverse across the recording paper. Thus all initial pulses are recognized by their position relative to the edge of the paper, and successive echoes from the ocean bottom or objects in the water may readily be correlated. Such a recording technique is generally accepted as a very powerful method for studying echoes from a bottom varying rapidly in depth, weak echoes against a noisy background and scattering from discrete reflectors over which the ship passes rapidly. This technique has made detailed investigations of submarine topography a practical venture, and has converted the taking of general ocean-depth soundings from a laborious task to an easy and continuous process.

Echo sounders providing this sort of information have been widely used since World War II. While the resulting soundings have greatly increased our knowledge of oceanic topography, these instruments have generally been less precise than is required for several problems. LUSKIN *et al.* (1954) have discussed these inadequacies and have described a recording system which corrects them by providing very accurate travel-time measurements. The recording system described below provides accurate travel-time measurements as LUSKIN's instrument does, and in addition provides considerably higher resolution for the purpose of studying the smaller-scale bottom-roughness features. For general bathymetric surveying we have also provided writing rates and ping lengths similar to existing deep-sea echo sounders. As this instrument was being developed several functions were also incorporated which make it useful for other marine-research problems involving acoustic travel-time measurements.

Among these is the tantalizing possibility of mapping subbottom structures at least to shallow depths, which has been repeatedly suggested by echo-sounder recordings showing excellent evidence of echoes from extended reflecting horizons below the bottom (e.g., see MURRAY, 1947). HERSEY and EWING (1949) have demonstrated the usefulness of distinguishing between reflections from the bottom and from subbottom horizons by filtering in several frequency bands ; the lower frequencies will penetrate the sediments to deeper horizons with far less attenuation than higher frequencies, so that deep reflections can be identified by the relative lack of high-frequency content. Thus a multichannel correlation recorder filtered in two or more frequency bands can be used to record reflections of complex pulses to provide a continuous section of subbottom structure just as single-frequency sounders provide a profile of the bottom.

Echo sounders have been used extensively to study the behaviour and occurrence of fish schools in shallow water (HODGSON and FRIDRIKSSON, 1955) and to study the animal populations of the open ocean by observing the characteristics of the deep scattering layers (DIETZ, 1948 ; HERSEY and MOORE, 1948 ; TUCKER, 1951 ; HERDMAN, 1953 ; and others). For these studies two different instruments are needed: one which will examine large volumes of water with each observation and possibly enhance the weak return from a sparse population, and a second having high enough resolution to single out individuals. The first requires slow writing rates on extended depth scales and, for echo enhancement, a long ping length. The second requires a very high writing rate and a very short ping length. It has been shown that scattering layers and individual fishes have frequency-dependent scattering ; hence multichannel recording is as useful in these studies as it is for reflection seismography. Thus the salient requirements for a recorder are similar in both fields.

THE RECORDER

Writing Speeds

Shallow-water instruments have high writing speeds (scales less than 100 feet across about 8 inches of recorded sweep, or ·005 seconds per inch), whereas deep echo sounders have medium to low speeds (100 to 6000 fathoms across 8 to 10 inches, ·025 to 1·5 seconds per inch). But no recording system has been available incorporating a range of choice between the two extremes. The writing rates of the first model of this recorder cover much of this overall range, while a second model provides only the slower writing rates needed for routine sounding (Table 1).

Stylus and Paper Drive

For a " stylus " we used a helical wire wound on a drum which rotates under a straight edge which is provided by an Aldin facsimile recorder. A positive-gear train driven by synchronous motors turns the helix drum by means of a cog-timing belt and also powers a simple friction paper-drive mechanism. Writing rates are selected by a multiposition switch which controls the speed and rotation sense of the motors, and shifts gears by means of magnetic clutches. The sixteen useable speeds of the first model were achieved by employing a differential at the output of two motors and their gear trains, while the second model employs only a single motor shaft (two speeds) and appropriate gear shift (Fig. 1). The paper drive has two speeds, one which advances the paper about the width of the recording trace per helix

revolution, and a second somewhat slower speed which has been found useful for integrating successive weak echoes or for aiding the correlation of echoes recorded when gated recording is used. We now feel that a third somewhat faster paper drive would be useful occasionally to permit the arrival time of single transient pulses to be unequivocally identified.

Table 1. *Recording speeds of the* 16*-speed drive* (*echo depth ranges based on sound velocity of* 4800′/*sec*).

Speed selection	*Depth range* (*fms.*)	(*ft.*)	*Helix* (*r.p.m.*)	*Sweep time interval* (*seconds*)	*Writing rates* 19″ *recorder* (*sec/in.*)	*Pulse lengths* (*seconds*)
1	20		1,200	1/20	·0027	·0003 to ·005
2	25		960	1/16	·0030	
3		200	720	1/12	·0044	Increasing
4	40		600	1/10	·0053	to
5	50		480	1/8	·0066	
6		400	360	1/6	·0084	
7	100		240	1/4	·013	
8	200		120	1/2	·026	·003 to ·05
9	400		60	1	·053	Increasing
10	500		48	1 1/4	·067	
11		4,000	36	1 2/3	·084	to
12	800		30	2	·106	
13	1,000		24	2 1/2	·13	·03 to ·5
14		8,000	18	3 1/3	·18	
15	2,000		12	5	·26	
16	4,000		6	10	·53	
			Recording speeds of the 6*-speed drive*			
1	200		120	1/2	·026	
2	400		60	1	·053	(See
3	500		48	1 1/4	·067	corresponding
4	1,000		24	2 1/2	·13	speeds above)
5	1,500		16	3 3/4	·2	
6	3,000		8	7 1/2	·4	

This sweep system has now been used on several ships on extended cruises, and has operated for periods of many days without adjustment.

Precision power source

For this purpose we have used a tuning-fork-controlled oscillator feeding a power amplifier. This equipment has scarcely been standardized ; the Ampex Model 375 and alternatively the Time Products, Inc. precision-power supplies have supplied precision 60 c.p.s. frequency control, while the Altec Model A287W 250-watt, and the MacKintosh K107 200-watt power amplifiers, have been used to drive the synchronous motors.

Recording Paper and Depth Scales

Both wet chemical-dye process papers and Teledeltos recording paper (a sandwich paper in which the carbonized inner layer is exposed by a spark discharge through the top layer) have been commonly employed. Recently Teledeltos paper has been greatly improved, but the grades employed in echo sounders smudge badly with

handling and will not display variations in sound intensity well. A further difficulty was the necessity for frequent readjustment of the stylus on several commercial models we used with the Teledeltos paper. Some of the wet chemical papers are apt to fade unless very carefully treated as they dry. However, a damp chemical-recording paper, ferrous-ion-deposit type (Alfax type A), had earlier shown promise for this sort of instrumentation since it does not fade and displays good response (several distinguishable tonal shades) to recording current changes ; consequently we experimented with it in this recording system. We used paper widths of 8 and 19 inches, but prefer the latter since it provides a wider recording surface and also feeds with less tracking problems in paper drive. Since the paper is damp and also since it changes dimensions (though linearly) upon drying, scales cannot be readily printed on it prior to use ; hence we record the depth scale simultaneously with the sounding data. The scale is printed by electrical pulses derived from the same precision source as the stylus and paper drive. Thus, these lines also indicate recorder synchronism, but calibration is accomplished by introducing a signal from a break-circuit chronometer and by the use of periodical time checks with a radio time standard.

Ping-Length Adjustment and Gating

The effectiveness of the recording technique depends in part on the choice of writing rates. However, the resolution is further dependent on the ping length, and the unambiguous identification of signals depends on the ability to gate or select a particular depth interval. For use with an echo sounder, the ping length is controlled by mechanical contactors on the recorder, the period of contact being adjustable between wide limits independent of writing rates (a minimum of about 0·3 milliseconds at the fastest writing rate in Table 1 and a maximum of 0·5 sec at the slowest). Thus at the fast rate, scatterers whose range differs by 1·5 ft. can be resolved ; at the slowest rate such a ping length as 0·05 sec is adequate for enhancing a weak signal by integration.

For gating, the outgoing pulse is actuated by the keying contacts which close once each revolution of the helix drum, and a second " selector switch " consisting of a twelve-contact commutator which rotates at one twelfth the speed of the helix drum. These contacts are, in turn, connected to the pinging circuit of the echo sounder through individual switches, so that any of twelve successive drum revolutions may be accompanied by a ping, or may not, as the operator desires. Similarly the helix wire may be connected to or disconnected from the amplifier which supplies the recording signal over the same twelve drum revolutions by another commutator. Thus it is possible to disregard reverberation from shallow scatterers in deep water by sending out pulses on only a fraction of the twelve sweeps, and recording only for the depth intervals where the bottom echo is expected. Conversely, the bottom echo can be disregarded and only the near-surface scattering recorded.

Multichannel Recording

Multichannel recording can be accomplished in three ways; (1) by providing as many helix wires on the same drum as there are channels of information; (2) by bridging the output of the several channels on to one helix all the time (this we already do when we record bottom echoes, depth scales, and time signals simultaneously) ; or (3) by causing the several channels to share time on the same helix. As a first design for

recording information filtered in several frequency bands we chose the last method and made a four-channel recorder simply by adding a quadrant commutator to the shaft of the helix drum, each quadrant being connected to one of four separate preamplifiers connected to the filters, which are connected, in turn, to the recorder driver amplifier. The four outgoing pings are actuated by four switches on the same shaft which close just as the recording circuit is switched from one channel to the next. Suitable interconnecting arrangements are made to provide one, two, or three channels, if desired. Also any of the four ping positions can be used singly.

This last feature is a great convenience when the recorder is used for conventional echo sounding. It is soon discovered in deep-water sounding that a particular depth of water will frequently occur near an integral multiple of the smaller depth scales (by the law of maximum unhappiness) thus placing the echo near one edge of the paper. By switching the ping to a quadrant that lies near the middle of the paper the echo is moved there as well.

APPLICATIONS

During its development the recording system was employed in a variety of ways which show its range of usefulness to marine science. These are described below with illustrative material, some of which was recorded at times when the design objectives had not been wholly achieved.

Travel-Time Measurement

The precision of travel-time measurements by the recorder depends on the precision with which the position of a recorded pulse can be determined relative to the timing lines recorded at the same time, as well as on the constancy of the sweep rate of the helix. The quality of both is shown in a recording of pulses one second apart from the time signal of Station *WWV* and from a break circuit chronometer (Fig. 2a). The beginning of each pulse can be determined readily to ·02 parts of the spacing between adjacent timing lines (0·05 sec apart) while the start of pulses from *WWV* form a line closely parallel to the time grid. Thus the record indicates that the power frequency in this case was constant and estimated to be within one part in 10^6 of 60 c.p.s. Thus for the time scales shown ($\frac{1}{2}$ sec across the record) a precision of $\pm$ ·0005 sec can be expected. Proportionately higher precision is available on the more expanded scales; with some writing rates, oscillations of the driving-gear train reduce the precision of the measurement below the limit set by resolution. Our power frequency has often differed from 60 c.p.s. by more than this (Fig. 2b), but holds a constant rate over long periods. Travel times can readily be corrected in such instances by measuring the slope of the chronometer trace (usually quite sufficient) or a radio time signal.

The accuracy of a given travel-time measurement depends on the shape and spectrum of the sound pulse and the signal-to-noise ratio as well as the precision of the recorder, and can be estimated only when these are known. Of course, the accuracy of any distance measurement (as depth in echo sounding) depends on one's knowledge of the travel path and sound velocity and is beyond the scope of this paper.

Application as an Echo-Sounding Recorder

There are several commonly observed features of bottom echoes. These include echoes having the same length as the outgoing pulse which occur either as long

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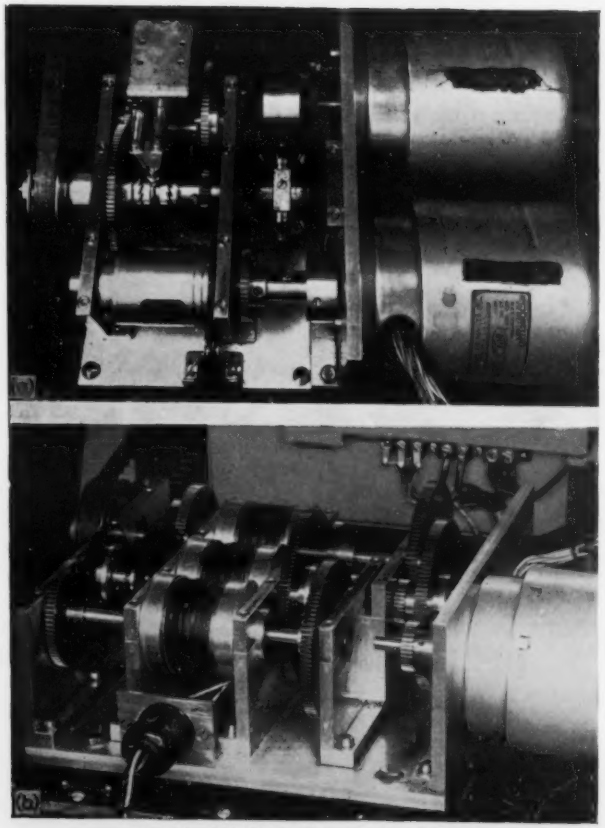

Fig. 1. Multispeed recorder drives :
(a) 16-speed gear assembly, (b) 6-speed gear assembly.

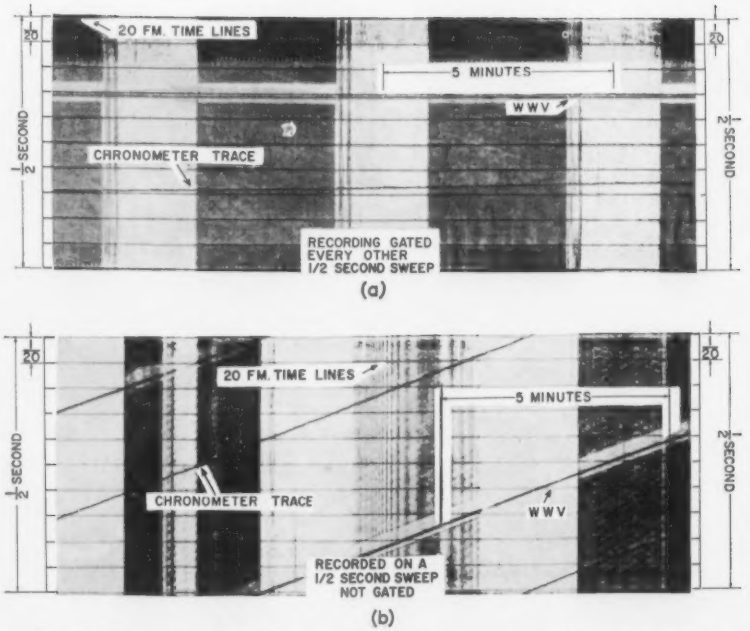

Fig. 2. Records of the timing grid and its calibration with a radio time signal and break circuit chronometer : (a) Precision power source close to 60 cycles, (b) Source constant but not at 60 cycles.

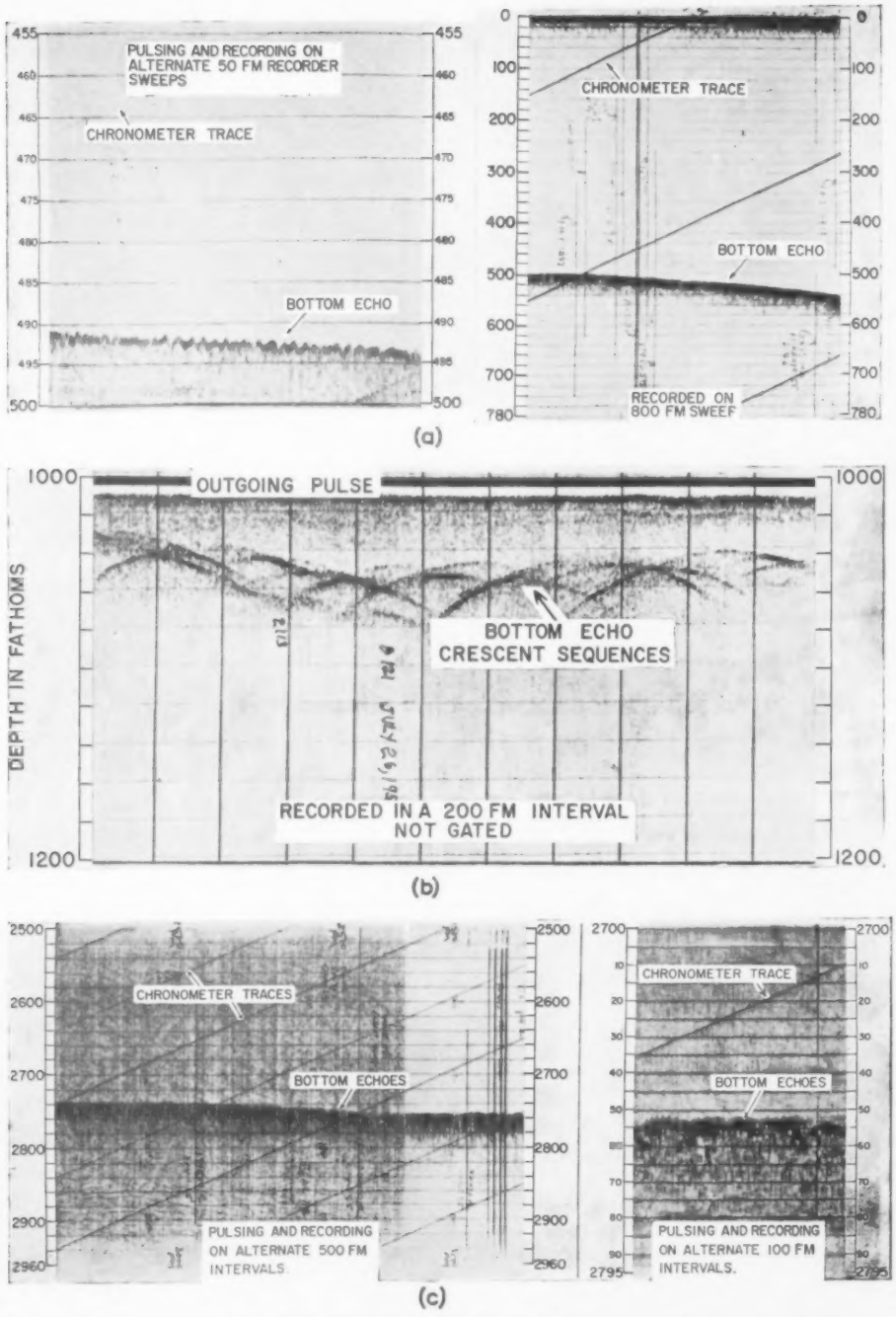

Fig. 3. Three examples of bottom roughness revealed by high resolution in various water depths. (a) 500 fm. – left, with an expanded scale, right, the same at lower resolution. (b) 1,000 fm. – with moderate resolution. (c) 2,700 fm. – left, low resolution ; right, the same with an expanded scale.

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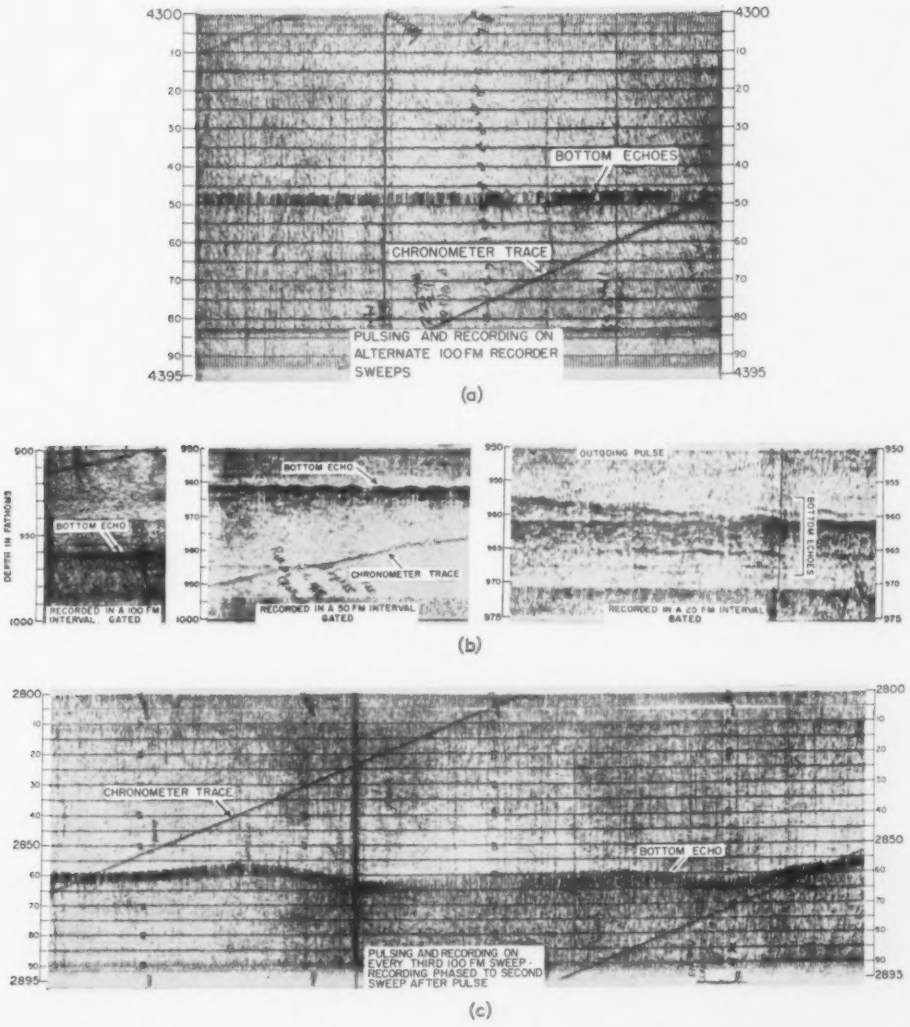
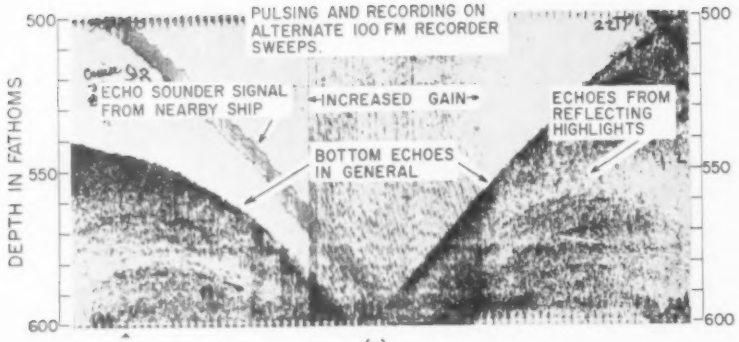
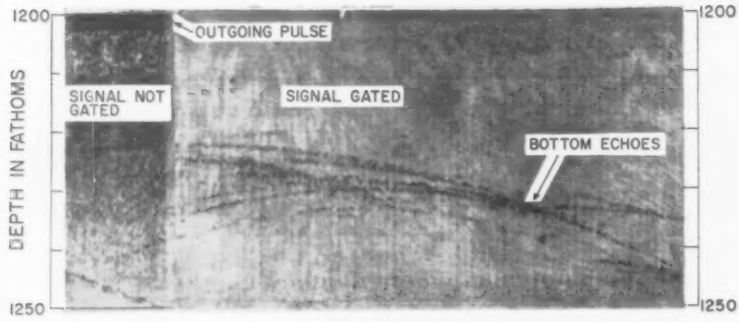


Fig. 4. Examples of high-resolution recording : (a) in the Puerto Rico Trench, (b) on a continental rise, (c) in an ocean basin.



(a)



(b)

Fig. 5. High-resolution recordings in Block Canyon : (a) a traverse of the canyon using the 100-fm. writing rate, (b) a portion of the canyon bottom on a similar crossing using the 25-fm. writing rate.

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sequences of closely correlated echoes (Fig. 3a), or shorter crescent-shaped sequences of echoes. The crescent sequences are interpreted as series of echoes from reflecting highlights on a rough bottom, the shape of the crescent being partly determined by motion of the ship relative to the highlight (Fig. 3b). These discrete echoes are usually accompanied by fainter, much more indistinct echoes as shown ; these signals sound like distinct echoes with very faint reverberation. Other bottom echoes have an intense portion equal in length to the outgoing pulse, which terminates more gradually. These sound like sharp echoes followed by reverberation of comparable intensity (Fig. 3c). Still other bottom echoes bear no resemblance to the outgoing pulse, and show little or no detailed correlation with each other. To the ear such echoes sound like a series of reverberations.

On a bottom appearing smooth when using the more usual recording speeds, we have recorded bottom echoes from shorter pulses and with higher resolution (e.g. Fig. 3a and c). In these examples the roll of the ship imposes its pattern, but, in addition (see especially Fig. 3c) the intense part of the echo sequence breaks up into more or less well-defined crescent sequences, and these are followed by fainter, rather patchy reverberation. The depth range of echo sequences having roughly the same darkness together with the approximate water depth can be used to compute the solid angle within which the strong highlights occur, and thus set a crude limit to bottom roughness. (Echoes from strong shoaler highlights, whose travel time is equal to or less than that of the principal group of bottom echoes, should reveal themselves by prolonged crescents like those in Fig. 3b). For Fig. 3a the ping length is roughly one fathom in a depth of about 500 fathoms. This record is somewhat complicated because the ship was under way and rolling, but crescents appear to form strongly over distances of, at most, about a fathom in depth, which corresponds to a cone of about 7 degrees. In 500 fathoms this corresponds to a circular patch of about 120 yards diameter from which echoes would not be completely resolved. However, the bottom echo is seldom strong for much longer than the pulse length. Hence the patch is probably even smaller ; a shorter ping length is needed to demonstrate how much smaller it may be. Similarly for Fig. 3c at a depth of 2752 fathoms the depth range encompassing the onset of all intense echoes is at most 6 or 7 fathoms, corresponding to a cone of about 8 degrees or a patch 1300 yards in diameter. Here again a shorter pulse would yield a more satisfactory estimate.

In a recording at moderately high resolution taken over a flat portion of the Puerto Rico Trench (Fig. 4a), the character of bottom roughness is especially interesting because of its great depth and its striking flatness. A 100-fathom gated scale was used with a ping length of about 3 fathoms. Here the undulations of the trace are due to the roll and pitch of the sounding ship, but the trace shows a clear bottom echo having the same length as the outgoing pulse, and is followed mostly by relatively weak reverberation. The variations in intensity suggest that an even shorter ping length and higher recording speeds would have brought out evidence of bottom roughness here.

Over a bottom recorded at 3 different resolutions (Fig. 4b) the 100-fathom scale shows a strong pulselike echo with complicated reverberation, and the more expanded scales show the principal reflection to consist of resolved echo sequences within the 3-fathom range covered by the ping length on the 100-fathom scale. Here the accom-

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panying patchy reverberation is frequently comparable to the principal echo. The usually fainter echoes whose travel times are shorter than the main group may have reflected from rough topography out to the side, or the whole complicated series could contain echoes from below the bottom ; with the present technique we cannot distinguish between these alternatives.

Study of the geomorphology of the ocean basin frequently hinges on reliably observing small changes of depth. High-resolution recording may reveal (Fig. 4c) these small changes in bottom depth and character even in very deep water. This recording was made east of the Bahamas, and possibly could be a depositional feature caused by density currents from the slope of the banks.

High-resolution techniques were used in an experimental study of Block Canyon in two cruises in 1954. The two recordings (Fig. 5) show the typical crescent-shaped highlights. The one at higher resolution shows how completely the echoes from the canyon floor are composed of highlights from individual reflectors. In an unpublished study of the crescent shapes of these canyon records, WILLIAM MOSS was able to show that some individual crescents come from reflectors of little horizontal extent while others are from extensive surfaces. We have been unable to return to this study since, but it appears that much could be deduced about the detailed shape of submarine canyons with a high-resolution echo sounder and very accurate navigation. An obvious extension of such observations would be to lower the echo sounder nearer to the bottom.

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Applications to Echo Ranging

The application of this mode of recording to echo ranging is straight forward ; it has been described in naval applications and is increasingly being employed for exploration by the fishing industry. We have made a series of observations in waters near Woods Hole on fish schools which illustrate the kind of information made available by high-resolution recording. The EDO echo sounder was used with the recorder as in the echo-sounding applications above, but with its transducer trained horizontally. Several fish schools were recorded over a smooth bottom in shallow water (Fig. 6). By suitable gating one of the schools was singled out for recording with a short pulse at high resolution (Fig. 6b). The rather formless mass (Fig. 6a) becomes a series of discrete echoes (Fig. 6b and c) that can be correlated over minutes of time.

Applications to Scattering-Layer Studies

Recordings of the scattering layers of the deep ocean have appeared many times in the literature, but in most instances from a transducer at the surface and with only the resolution required to show the layered character. KANWISHER and VOLKMANN (1955) have described observations using an EDO echo sounder with the transducer lowered below the ship. They observed some individuals that could be resolved even with the 100-fathom scale of the EDO recorder. JOHNSON *et al.* (1956) have continued this line of investigation through several stages in the development of the Woods Hole Oceanographic Institution recorder, and have been successful in observing the movement of individuals in a layer during its migration, using high resolution. They have also photographed individuals which had first been " located " by means of the echo sounder.

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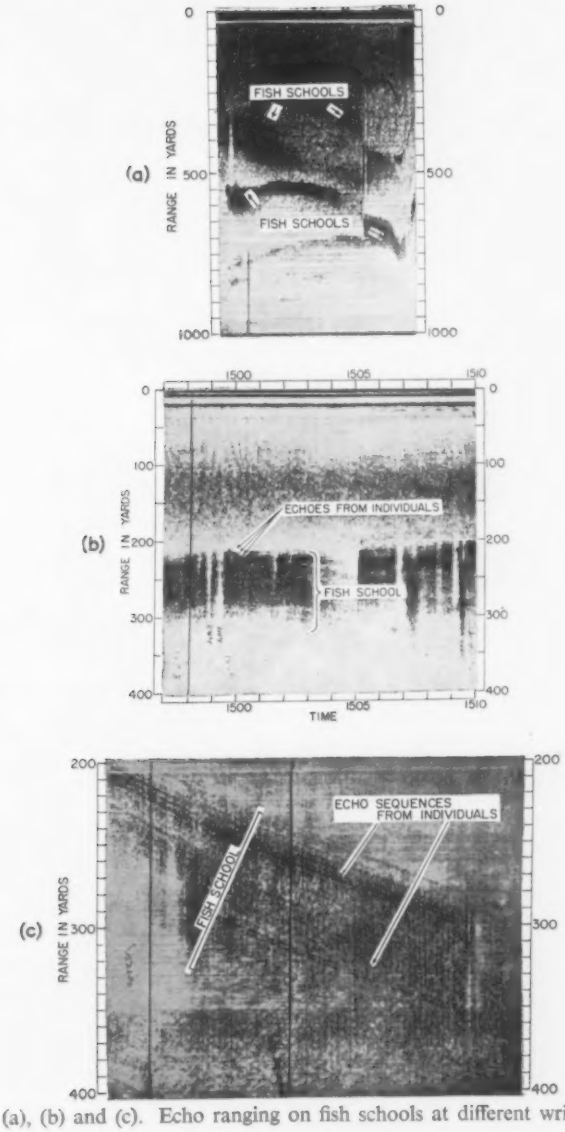

Fig. 6. (a), (b) and (c). Echo ranging on fish schools at different writing rates.

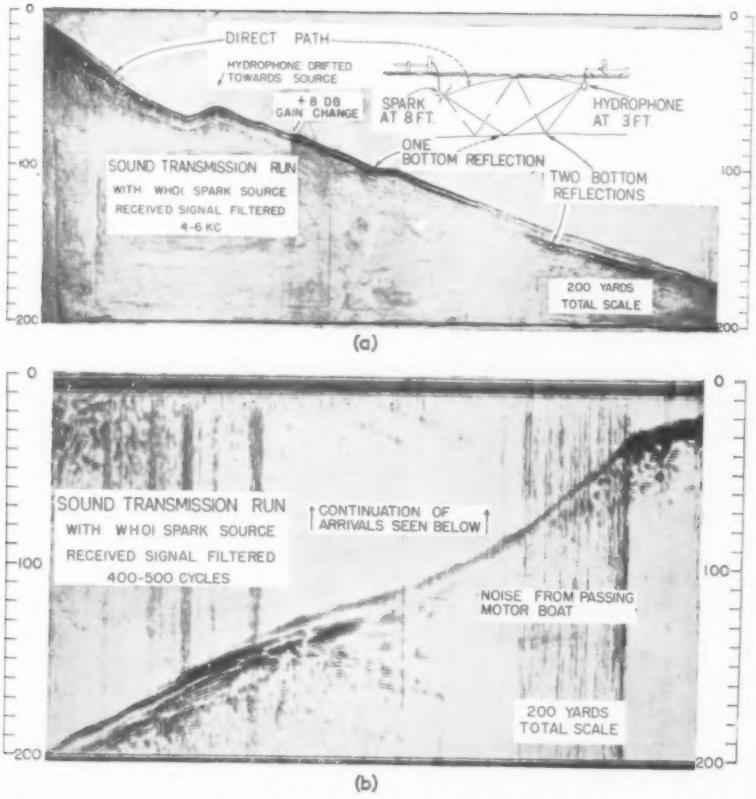

Fig. 7. (a) and (b). A sound transmission study in Great Harbor, Woods Hole.

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Applications with a Sound Source having a Broad Spectrum

The applications described thus far have employed a single-frequency sound source. We have incorporated an electric spark discharged under water as a sound source in order to study frequency-dependent effects. The output of the sparker is usable over the range from 0.1 to 50 kc, and offers the possibility of studying in a more detailed way a range of problems which have been studied in the past, using explosives as sound sources. Typical examples are geologic structures at shallow depths below the bottom ; details of multiple-path transmission through the water where the travel times involved are nearly, but not quite, equal ; and the frequency-dependent properties of marine sound scatterers. The combination of the spark with the recorder is a powerful method for observing both short- and long-period variations in these phenomena. It can also be used in conjunction with an A-scan oscilloscope and camera for sound-intensity measurements, with the recorder acting as continuous observer for determining when 'scope photographs should be taken.

A recording was made of the underwater transmission from the sparker at the institution's dock to a hydrophone towed by a rowboat to distances of the order to 200 yards (Fig. 6). The spark sound pulse is emitted when the helix starts its sweep near the edge of the paper, and sound received over various paths is recorded as it arrives at the hydrophone. The first recording (Fig. 7a) was made through a 4-to-6-kc band-pass filter. The first arrival noted at the shorter ranges is transmitted directly through the water, and it is double owing to the bubble pulse from the spark. The second group of arrivals is a single bottom reflection which is somewhat complicated, the principal features being four arrivals near its leading edge. Two of the arrivals are the initial sound and bubble pulse, while the others are related to them by travel-time differences to be expected from bottom-reflected travel paths directly from the spark and, after one reflection, from the surface near the spark. (The spark was 8 feet below the surface ; the hydrophone, 3 feet). The third group of arrivals corresponds to paths involving two reflections from the bottom ; they are seen to be weakly developed over most of the experiment, but do come in strongly at certain ranges. Subsequent repeats of the same test showed this intensification to be reproducible. A similar run was recorded through a 400-to-500-c.p.s. band-pass filter (Fig. 7b). While the same general features can still be seen, they are not as readily resolved because of the lower frequency, but the more striking contrast between the two frequency bands is the appearance of a complicated set of arrivals at the lower frequency, which come in later than those mentioned above and which have no counterpart in the higher-frequency recording. These may well be reflections from below the bottom where the higher frequencies are very rapidly attenuated. In other test observations we have recorded scattering from fish schools in Vineyard Sound at both low and high frequencies, and have recorded consistent low-frequency echoes having no high-frequency counterpart, which have the appearance of coming from a reflecting surface below the bottom. On another occasion off the coast of South Carolina a subbottom echo was recorded with the multichannel recorder described above ; it appeared strongly on a low frequency channel, but not at all on a high-frequency channel.

From these two observations and other tests we find the recorder satisfactory, but the spark source rather too weak for any other than short range phenomena.

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Applications to the Locations of Instruments

BACKUS and HERSEY (1956) determined the shape of a trawl wire with a standard Edo echo sounder. Similarly other objects of sufficient target strength have been tracked to depths of several hundred fathoms. Sonobuoys have been located for retrieving at a range of three miles by pointing the Edo transducer horizontally and recording the radio transmission of the sound received at the buoy. The buoy used was not intended for this purpose ; a sonobuoy of suitable design could be located at considerably greater ranges.

Acknowledgements—We are indebted to several members of the staff of the Woods Hole Oceanographic Institution for suggestions and assistance in the design, construction, and testing of the recorder. We are especially indebted to the instrument-shop staff of The Woods Hole Oceanographic Institution for their interest in the construction of the gear drives and their help in meeting cruise deadlines. MR. WARREN WITZELL made many valuable contributions to the mechanical design, and MR. HERBERT SMALL developed the principal electronic components such as the pre-amplifiers and power amplifier feeding the recording stylus, and the timing-grid generator.

The recorder was developed and tested at sea under Contract NObsr-43270 and NObsr-72521 with the Bureau of Ships.

Contribution No. 863 *of the Woods Hole Oceanographic Institution.*

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The frequency distribution of surface-water characteristics in the Pacific Ocean

JOHN D. COCHRANE

Abstract—The frequency distributions of surface-water characteristics in the Pacific Ocean are presented in a series of temperature-salinity diagrams. The frequencies are estimated from maps of mean surface temperature and salinity in February and August. Six twodimensional distributions are obtained, one each for February, August, and the year in the North Pacific, and one for each of these periods in the South Pacific. Prominent features of the distributions are discussed.

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ALTHOUGH many maps and tabulations have been prepared to show the geographical distribution of average sea-surface temperature and salinity, few attempts have been made to describe the prevalence of different temperatures and salinities at the sea surface. The aim of the present study is to determine the prevalence of these properties at the surface of the Pacific Ocean. Six frequency distributions are derived, one each for February, August, and the year in the North Pacific, and one for each of the same periods in the South Pacific.

Nearly all previous studies of prevalence have been confined to temperature. Sir JOHN MURRAY (1898) obtained for each ocean the area of sea surface having maximum and minimum temperature within 10°F intervals. SPILHAUS (1942) computed the percentage of ocean surface having annual mean temperatures within various 5°C temperature intervals. A very complete series of sea-surface temperature distributions based on modern charts is given in a manuscript prepared by W. H. LITTLEWOOD of the US Navy Hydrographic Office*. Distributions of area among 5°F temperature intervals are presented for February and August in the world ocean and in each ocean separately.

Prevalence of both temperatures and salinities over large areas of the ocean surface does not appear to have been considered previously. The method, used by HELLAND-HANSEN (1926) and others, of plotting large numbers of serial observations of temperature and salinity from a given area as a scatter diagram (in temperature-salinity co-ordinates) gives some suggestion of the twodimensional frequency distribution. But, of course, the observations are almost never uniformly spaced horizontally or vertically. While not directly concerned with prevalence, WÜST, BROGMUS and NOODT (1954) presented related information. They showed, in a series of temperature-salinity diagrams, the average annual temperatures and salinities for each 5° zone of the world ocean and of each ocean separately. MONTGOMERY (1955) dealt quantitatively with the twodimensional frequency distribution of surface temperature and salinity at Weather Ship J.

In discussing the present study, it is convenient to introduce a few definitions. As in MONTGOMERY's paper, the term characterstic denotes a point on the temperature-salinity diagram. Characteristic class refers to the area on the diagram included in

*This manuscript, entitled " Surface Water Temperature Distribution of the World", and dated April 1955, was brought to the writer's attention by Mr. JOHN LYMAN, Chief, Division of Oceanography, US Navy Hydrographic Office.

a specified temperature and specified salinity interval. The frequency of a characteristic class means its prevalence in extent and duration within the region and period considered.

The boundaries of the North and South Pacific Oceans follow those given in *Die Grenzen der Ozeane und ihre Nebenmeere* (Anon., 1939). Adjacent seas are included. Sea-surface water in both ice-free and ice-covered areas is considered. In the latter areas, the term " sea surface " becomes ambiguous. Here it is used to denote the under-surface of the ice.

Ideally, an estimate of the frequency distribution of characteristics for a selected period and region would be based on a long, uniform series of observations from many fixed points spaced in relation to average gradients. Such ideal data do not exist, and even approaching them with existing observations involves considerable difficulty. Consequently, as a quick method of obtaining a first approximation, the distributions of the present study are based on information available in published form, maps of average conditions. While this procedure has obvious limitations, it seems unlikely that the salient features of the distributions so derived are untrue.

SCHOTT's (1935) maps of temperature and salinity are used as basic information except for the Antarctic region. There the more recent information in DEACON's (1937) maps of salinity and MACKINTOSH's (1946) maps of temperature seem preferable. Because of the scantiness of data from the Antarctic, especially in ice-covered areas, contributions of this region seem least reliably evaluated.

The temperature range was divided into a series of 2°C intervals beginning with −2° to 0°C, and the salinity range into intervals of 0·4‰ beginning with 29·2 to 29·6‰. This resulted in 16 intervals to cover the temperature range and 19 intervals to cover most of the salinity range encountered in both oceans. Areas having salinities below 29·2 and above 37·0‰ are negligibly small.

Between 20° and 50° latitude, both north and south, regions of large horizontal gradient, the ocean surface was divided into areas 2½° latitude by 5° longitude ; in other latitudes, into areas 5° latitude by 5° longitude. Near coast lines and in a few regions of large horizontal gradient, the above areas were subdivided into as many as four equal sections. Both for the North and for the South Pacific, the total of all these small areas agrees to 3 figures with the values given by WÜST, BROGMUS, and NOODT (1954, page 139).

For February and for August, the area mean characteristics of each small area were estimated visually in terms of the centre values of the characteristic classes. The area distributions were obtained by summing the small areas within each characteristic class. These area distributions are used as approximations to the frequency distributions, although frequency as defined above includes duration as well as extent. While somewhat too concentrated, the approximations seem reasonably good, since the local range of characteristics during a month is generally not nearly so large as the total range for an ocean, but is comparable in size with the class intervals used (2°C and 0·4‰).

For the year, however, duration must be taken into account in the frequency distributions. Unfortunately, local distributions are very inadequately known. MONTGOMERY (1955) obtained the distribution at Weather Ship J in the North Atlantic. But this does not seem to be typical of large areas of the Pacific Ocean. As a first approximation, it was assumed in the present study that the characteristics

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at a fixed location all lie between the February and August mean values and occur with equal frequency. This gives distributions which are flatter than the actual distributions and cover a smaller range, since characteristics outside of the extreme monthly means actually occur.

The frequency distributions for the winter month, the summer month, and the year are presented in the temperature-salinity diagrams of Figs. 1, 2, and 3, respectively. Smooth isopleths were entered in each diagram to suggest the shape of the continuous frequency surface $z = f(S, T)$. They also serve to emphasize the differences between the North and South Pacific, and between winter and summer. While the isopleths were drawn so as to be smooth, they fulfill roughly the requirement that for each characteristic class the average ordinate of the frequency function $f(S, T)$ be equal to the discrete frequency for the class. Expressed symbolically, the requirement is that

$$N_{ij} = \frac{1}{\Delta S \cdot \Delta T} \int_{S_i}^{S_i + \Delta S} \int_{T_j}^{T_j + \Delta T} f(S, T)\, dT dS,$$

where N_{ij} is the frequency of the characteristic class defined by the salinity interval extending from S_i to $S_i + \Delta S$ and the temperature interval extending from T_j to $T_j + \Delta T$. The isopleths thus appear as contours based on the discrete frequency values.

All of the frequency distributions have one general form, a ridge of higher frequencies running from low temperature and low salinity to high temperature and high salinity, and then to lower salinity at about the same temperature. The ridge might be described as having the shape of a " seven " lying on its right side. (The means for 5° zones of the North and South Pacific given by WÜST, BROGMUS, and NOODT (1954) fall nearly along the ridge lines of the annual distributions.) Along the ridge, there are two or three appreciable peaks. The strongest of these occurs in all cases at the angle of the " seven," that is, at rather high temperature and salinity. (Although the South Pacific distribution for August has its highest value at low temperature, the bulk of high frequencies are at high temperature). The range of frequency values between peaks and low points along the ridge is quite large. A striking feature common to all the distributions is the fact that temperatures and salinities between the two branches of the ridge have nearly zero frequencies.

There are, of course, many marked differences between the distributions for the North and South Pacific, in addition to the well known difference in salinity range. (1) The maximum at high temperature is much stronger in the North Pacific distribution than is the one for the South Pacific. For the former, both August and February have single characteristic classes with frequencies higher than 14 per cent! This clearly results from the fact that the North Pacific is wide at low latitudes, where temperatures are generally high, and narrow at high latitudes. (2) The South Pacific distributions have marked maxima at low temperature because of the inclusion of the Antarctic area. (3) The North Pacific distributions, on the other hand, have distinct secondary frequency maxima at high temperature and low salinity because of the extensive areas of low salinity near the coasts at low latitudes in the Northern Hemisphere and near the intertropical convergence zone which usually lies in the Northern Hemisphere.

An interesting quantitative comparison between the distributions can be made by computing for each distribution the proportion of the total frequency enclosed

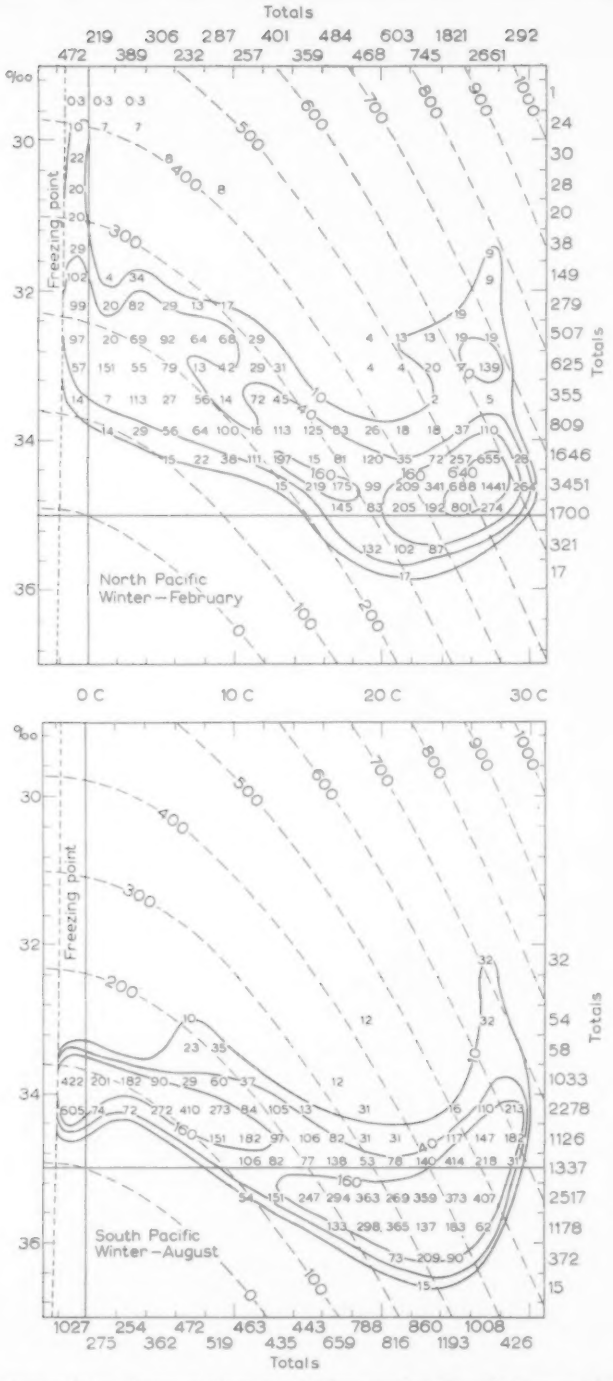

Fig. 1. Temperature-salinity diagrams showing the frequencies of surface-water characteristics for winter, February in the North Pacific, and August in the South Pacific Ocean. In each diagram, the sum of the frequencies is 10,000. Smooth isopleths of frequency are entered as full drawn curves. The frequency values may be converted to area by multiplying by 816 km² for the North Pacific or by 981 km² for the South Pacific. Isopleths of anomaly of specific volume are shown as dashed curves. Their values are given in centiliters per ton (metric).

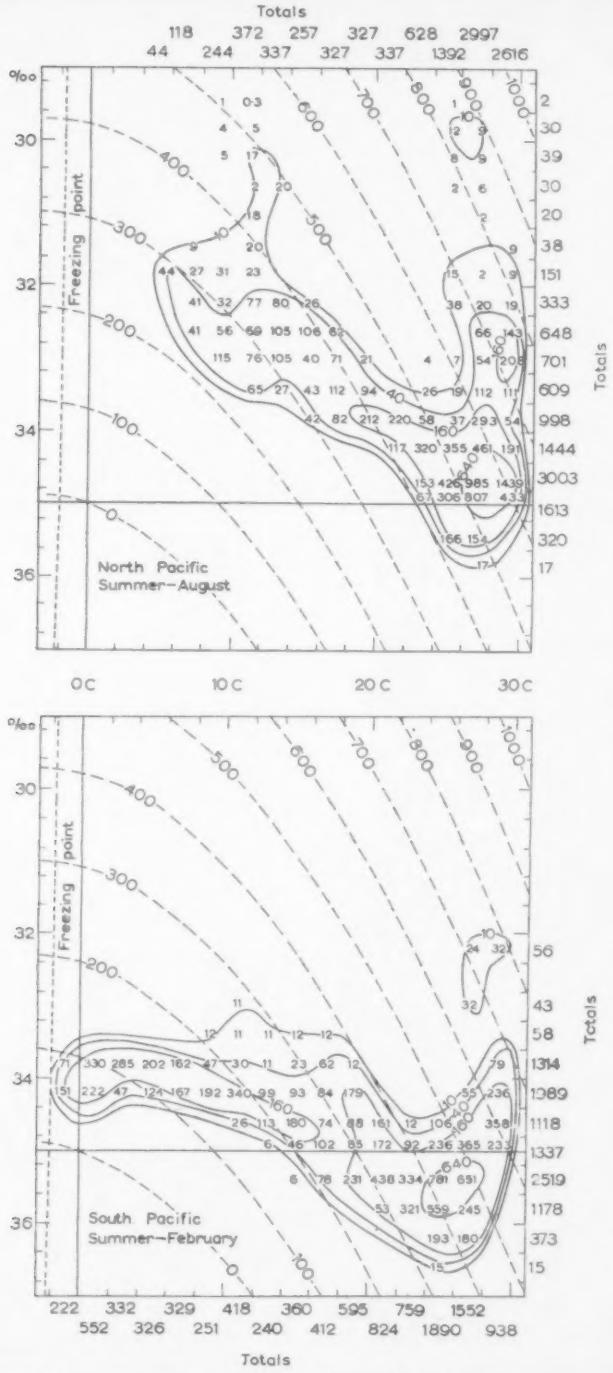

Fig. 2. Temperature-salinity diagrams showing the frequencies of surface-water characteristics for summer, August in the North Pacific, and February in the South Pacific Ocean. In each diagram, the sum of the frequencies is 10,000. Smooth isopleths of frequency are entered as full drawn curves. The frequency values may be converted to area by multiplying by 816 km² for the North Pacific or by 981 km² for the South Pacific. Isopleths of anomaly of specific volume are shown as dashed curves. Their values are given in centiliters per ton (metric).

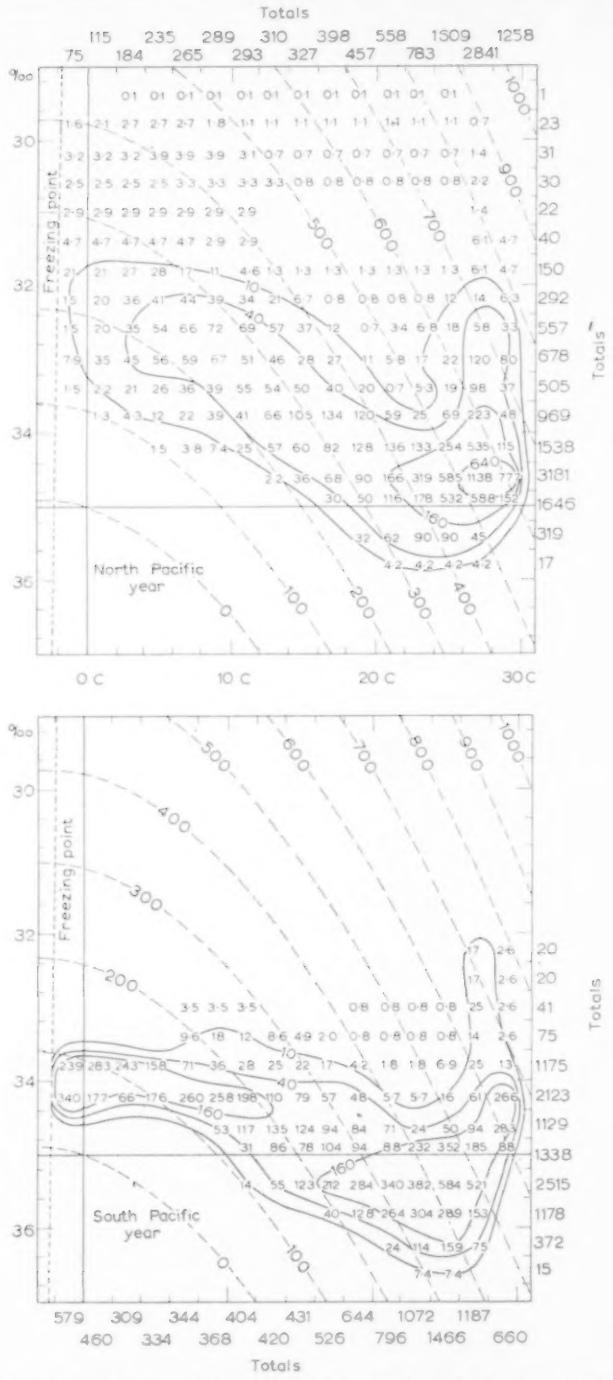

Fig. 3. Temperature-salinity diagrams showing the frequencies of surface-water characteristics for the year in the North and South Pacific Oceans. In each diagram, the sum of the frequencies is 10,000. Smooth isopleths of frequency are entered as full drawn curves. Isopleths of the anomaly of specific volume are shown as dashed curves. Their values are given in centiliters per ton (metric).

within given frequency isopleths. For want of a name, this quantity was called "beta" by MONTGOMERY (1955), who obtained isopleths enclosing stated proportions of the total. The approximate proportions for the isopleths entered in Figs. 1, 2, and 3 are given in Table 1. In both oceans, the distributions are most concentrated in the summer month, less concentrated in the winter, and, of course, least concentrated for the year. However, the oceans differ markedly in peakedness. Much of the North Pacific distribution is concentrated very near the modes, 19% of the total lying within the 640 isopleth even in the annual distribution. The concentration very near the modes of the South Pacific distributions is much less. In summer, 20% lies within the 640 isopleth compared with 34% for the North Pacific. And in the winter and annual distributions for the South Pacific, there is no 640 isopleth. On the other hand, the South Pacific shows consistently higher proportions within the 160 isopleth.

Table 1. *Proportion of the total frequency enclosed within selected frequency isopleths in per cent.*

Frequency Isopleth	*North Pacific*			*South Pacific*		
	August	*February*	*Year*	*February*	*August*	*Year*
640	34	25	19	20	0	0
160	64	55	46	80	74	72
40	90	85	80	92	88	88
10	95	92	90	93	92	91

Many smaller features of the frequency distributions might be sorted out and related to features of the geographical distributions. Some caution, however, must be exercised in interpreting the very small features because of limitations in the source information and the methods used. The actual distributions are undoubtedly smoother than those presented here. It is partly for this reason that smooth isopleths of frequency were entered in the diagrams. Some bumpiness, however, is to be expected in the actual distributions, since water with a narrow and unusual range of characteristics may occur in relatively isolated portions of the ocean.

The onedimensional frequency distributions of temperature and salinity obtained by summing columns and rows, respectively, in each of the temperature-salinity diagrams of Figs. 1, 2, and 3 are entered along the outer edges of the diagrams. The distributions of anomaly of specific volume are given in table 2. They were derived by adding the frequencies lying between the isosteres shown in Figs. 1, 2, and 3. Because of this indirect method of derivation, the accuracy of these distributions is less than that of the temperature and salinity distributions.

All of the distributions of temperature have a strong mode at high temperature. All but the North Pacific annual distribution have a second, smaller mode at low temperature. This mode is marked in the South Pacific distributions because of the inclusion of the Pacific Antarctic region. It is distinct, though small, even in the North Pacific, where its temperature undergoes considerable seasonal variation. A third, very weak mode occurs between 8° and 12°C in the South Pacific distributions. A faint suggestion of this mode occurs in the North Pacific distribution for February.

The distributions given by LITTLEWOOD are similar to those presented here. Even the third mode appears in the South Pacific distribution.

All of the salinity distributions are bimodal. The North Pacific has a strong mode at rather high salinity and a weak one at relatively low salinity. In the South Pacific distributions, the range of salinity is much smaller, the modes are closer together, and the mode at higher salinity is only slightly more intense than the one at lower salinity. For the South Pacific, the modes correspond to the two principal modes of the twodimensional distribution. But for the North Pacific, only the strong salinity mode corresponds to the principal twodimensional mode. The weaker mode at lower salinity results from both the high and low temperature branches of the twodimensional distribution.

Table 2. Frequency distribution of specific volume anomaly, in per cent.

	Anomaly of Specific Volume, in cl/ton								
	0 to 100	100 to 200	200 to 300	300 to 400	400 to 500	500 to 600	600 to 700	700 to 800	800 to 900
North Pacific									
February	0·1	10·0	21·2	13·3	21·3	28·7	5·2	0·2	0·0
August	0·0	0·0	4·9	11·2	20·4	32·7	25·0	5·1	0·7
Year	0·0	3·7	13·6	16·2	21·2	32·3	11·3	1·5	0·2
South Pacific									
February	6·5	17·6	11·1	28·1	22·5	8·3	5·3	0·6	0·0
August	15·0	24·4	21·4	14·1	15·4	6·1	3·3	0·3	0·0
Year	10·0	20·4	17·3	19·9	20·6	6·1	5·4	0·3	0·0

The distribution of specific volume anomaly is bimodal except for August and the year in the North Pacific. The modes correspond to modes in the two-dimensional distributions except that the high-temperature, low-salinity mode of the North Pacific distribution does not result in a mode in the specific volume anomaly distribution, but only in a tailing off toward high values.

Perhaps the principal value of this inventory of temperature and salinity conditions at the surface of the Pacific Ocean is that it puts into perspective some of the many details encountered in working with sea-water characteristics. A systematic classification of Pacific Ocean waters can hardly be made without this and a similar inventory of subsurface temperatures and salinities. Such information is essential to a quantitative study of the evolution and maintenance of water characteristics.

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Scripps Institution of Oceanography, University of California.
La Jolla, California.

Present affiliation: Department of Oceanography and Meteorology, Agricultural and Mechanical College of Texas.

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Studies of the deep water fauna and related problems

L. A. ZENKEVICH and J. A. BIRSTEIN

Abstract—1. Investigations on the Kuril Trench, carried out in 1953 by the Soviet expedition on the Research Ship *Vitjaz* allowed several general principles to be laid down in the change of the bottom and the pelagic faunas with increasing depth.

2. The biomass of benthos and plankton in the ultra-abyssal zone (> 6,000 m) is 1,000 times less than in the surface zone.

3. With the increase of depth the variety of species of benthos decreases ; its diversity increases at first and then decreases, for the most part within the ultra-abyssal zone.

4. The colouring change of bottom and pelagic animals also takes place differently according to depth. Many pelagic animals are pigmented up to depths of 6-7,000 m. Only the plankton of the ultra-abyssal zone is totally devoid of pigment (except the amphipad *Andaniexis subabyssi* Birst. et M. Vin.). The bottom animals become pigmentless, at depths greater than about 2,000 m. Possibly this dissimilarity is due to vertical migrations of broad range peculiar to pelagic animals.

5. The relative importance of predators of plankton increases with depth. This contrasts with the bottom animals, for which there is an increase in relative importance of detritus eaters and a lesser importance of predators at increasing depths.

6. One of the many sources of food supply for the abyssal and ultra-abyssal fauna is provided by the transportation of organic matter from the zone of photosynthesis down to the great depths by means of vertical migration of zooplankton, performed either within each fixed vertical zone, or having a still broader range. During their vertical migrations the upper layers of deep-sea animals become the prey of the lower dwellers and thus the organic matter produced in the zone of photosynthesis is brought to the greatest depths of the ocean.

7. The body-size comparison of species of the same genus inhabiting different depths shows a tendancy to greater body-size with greater depth. This is true for both bottom and pelagic animals. It cannot be explained by temperature changes.

8. The deep-sea fauna comprises a great quantity of ancient and primative forms.

9. The zoogeographic regions of the ocean ought to be determined from separate vertical zones. In addition, the determination of zoogeographic regions of the abyssal zone will show not only the connections and the hydrological regime of the contemporary seas and oceans but also those of the seas and oceans of the remote past.

10. The ultra-abyssal faunas of each trench must comprise endemic species or even units of a higher taxonomic grade. A set of these species was discovered in the extreme depths of the Kuril Trench.

INVESTIGATION of faunas inhabiting the great depths of the ocean only started in the last half of the 19th century and until recently has been confined to depths of less than about 6 km. In the last seven years, however, new and extensive material has been obtained on the deep-water fauna of all oceanic depths down to the greatest, of more than 10 km. These collections were made mainly by two expeditions: the Soviet expedition on the *Vitjaz* (started in 1949) (Fig. 1) and the Danish expedition on the *Galathea* (1951-1952). The *Galathea* has explored several deep-sea depressions in different parts of the ocean, but only in respect to their bottom fauna and bacteria.* The work of the *Vitjaz*, though confined to the north-western Pacific and bordering seas, embraces a complex of oceanographic research, including biological investiga-

* *Galatheas Jordomsejling* 1950-52, 1953. Under redaction of BRUUN, GREVE, MIELCHE and SPÄRCK.

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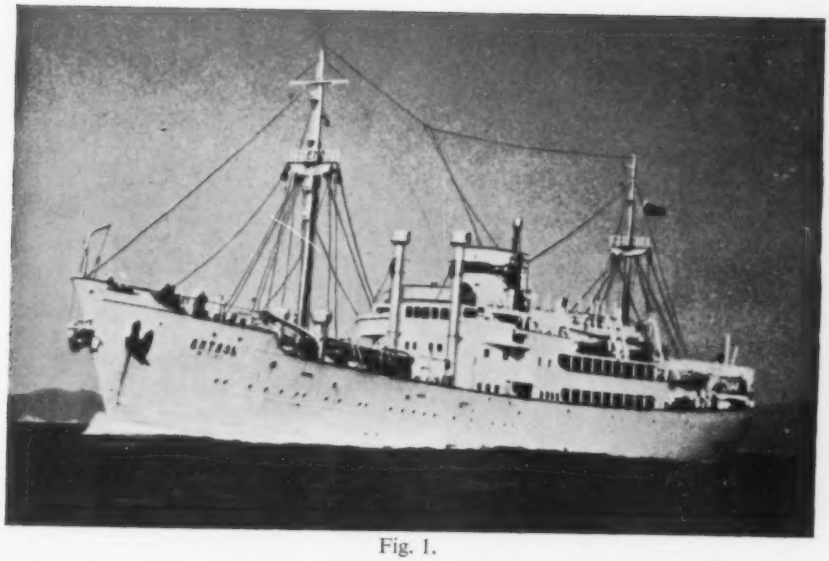

Fig. 1.

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tions. A detailed study of the Kuril Trench involving its whole water mass as well as its floor down to the greatest depths, has revealed some important peculiarities in the vertical and horizontal distribution of life through the whole immensity of its 10 km deeps.

Table 1. *Vertical faunistic zones of the ocean.*

Zones	*Subzones*	*Depth (m)*	*Percentage of the whole surface area of the World Ocean*
Surface	littoral	over 0	0·004
	sublittoral	0–200	7·6
Transitional		200–600	3·5
Abyssal	upper abyssal	600–2,000	5·0
	lower abyssal	2,000–6,000	82·7
Ultra-abyssal†		6,000–10,862	1·2

To begin with, the north-western Pacific is characterised by what appears to be a rather rich deep-water fauna. Nineteen species of pogonophores have been recorded, ten species of echiurids, some scores of amphipod species, echinoderms, especially holothurians and many others. Future investigations will show whether these findings reflect a real quantitative diversity of the deep-water fauna of the Kuril Trench, or whether they are merely the result of the very thorough investigations carried out by the *Vitjaz*.

Table 2. *Changes of biomass of zooplankton with increasing depth* (*after* VINOGRADOV, 1954).

Horizon (m)	0–50	50–100	100–200	200–500	500–1,000	1,000–2,000	2,000–4,000	4,000–6,000	6,000–8,000
Biomass (mg/m³)	497·6	320·3	246·6	228·0	59·3	21·8	9·3	2·64	0·48

Table 3. *Changes of the biomass of benthos with increasing depth* (*after* ZENKEVITCH, BIRSTEIN *and* BELJAEV, 1955).

Depth (m)	950–4,070	5,070–7,230	8,330–9,950
Biomass (g/m²)	6·94	1·22	0·32

The material obtained permits a scheme to be drawn of the vertical zoning in the distribution of oceanic faunas. The scheme, originally suggested for the plankton

† For the deep zone over 6,000-7,000 m and the fauna populating it, ZENKEVITCH put forward in 1953 terms such as: super-oceanic depths and superdeepsea fauna. BIRSTEIN (1954) preferred terms: ultra-abyssal zone and ultra-abyssal fauna. BRUUN (1956) proposed the term: hadal.

organisms (BIRSTEIN, VINOGRADOV and TCHINDONOVA, 1954) was found to apply also to benthos and nekton.

Thus the living space occupied by the deep-water fauna is far greater than all the rest of the biosphere and extends over two-thirds of the whole Earth's surface.

Considering the changes occurring in the benthic and pelagic fauna with increasing depth, we discover some striking features of similarity and dissimilarity. First of all we notice the similar characteristics of decrease of biomass with increasing depth. The following indices, illustrating this phenomenon, were obtained for zooplankton and benthos of the Kuril Trench (Tables 2 and 3).

Considering that on the continental shelf of the north-western Pacific the benthic biomass is expressed by a value of some hundred g/m² we must admit that the biomass of plankton and benthos undergo a similar decrease when reaching the ultra abyssal zone, i.e. they diminish by about 1,000 times.

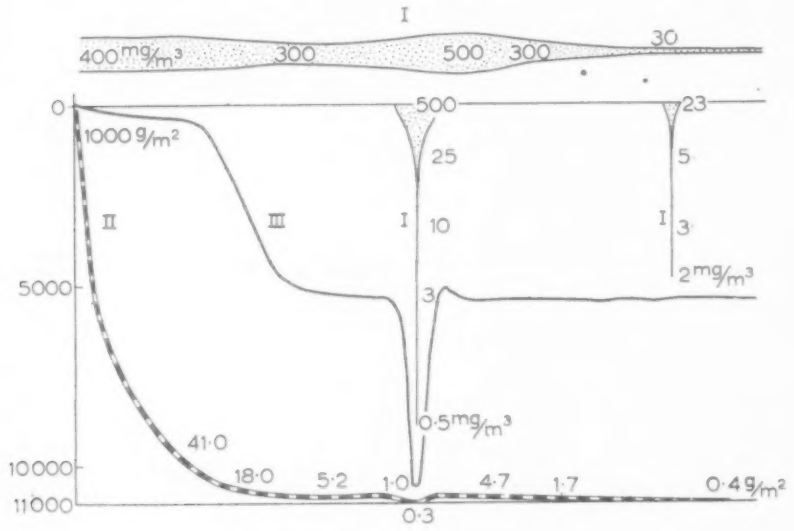

Fig. 2.

The foregoing remarks are well illustrated by Fig. 2 showing a section through the Kuril Trench and the adjacent part of the Pacific (III), with the characteristic biomasses of plankton (I) and benthos (II)* of this region. The biomass of surface plankton is expressed by a value of 300-500 mg/m³ over a considerable area, but it increases abruptly in the region of the junction of warm and cold waters and drops to some few mg/m³ in the zone influenced by the warm Kuroshio waters. The decrease related to depth is still more abrupt. The biomass of benthos also decreases with depth, but, in this case, contrary to that of the plankton there is also a regular decrease with distance from land, observed even on stations taken at identical depths. This is determined by a lesser supply of food, since the nutrient material is produced in the coastal zone and brought by outflow from land.

*The scale of the ordinate bears no relation to the benthos biomass curve (II), but correlates with the bottom relief mass curve (III) only.

If we consider the variations related to depth, of some qualitative indices of the fauna, we find very striking differences between benthos and plankton, and, first of all in the number of species (Fig. 3). It has been demonstrated for several systematic groups of bottom animals, that their diversity decreases with depth.

If we take the total number of species in each systematic group as 100 per cent, this decrease will be expressed by the following indices (Table 4).

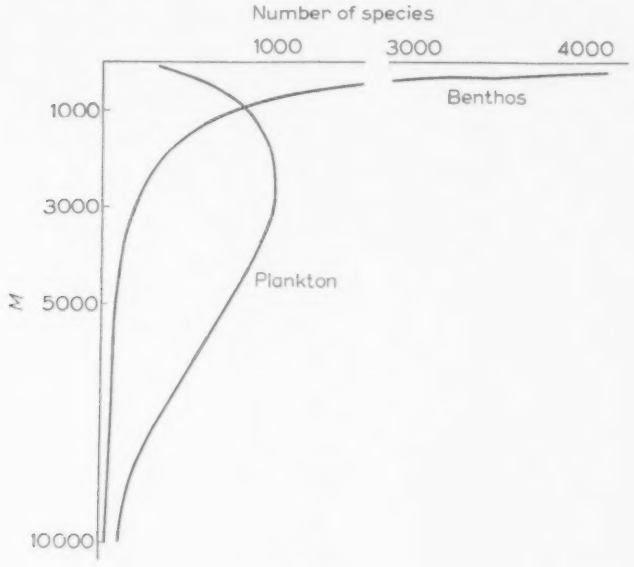

Fig. 3.

*Table 4. Relative specific variety of some groups of bottom animals (percentage of total number of species).**

Depth (m)	*Over 1,000*	*Over 2,000*	*Over 3,000*	*Over 4,000*	*Over 5,000*
Hydroidea	?	?	0·4	0·4	0·2
Polychaeta	?	3·7	2·6	1·7	0·6
Peracarida	?	1·3	?	?	?
Pantopoda	?	9·7	4·5	1·5	?
Bryozoa	?	?	1·2	0·4	0·1
Crinoidea	21·6	7·7	2·9	1·8	0·5
Echinoidea	18·7	?	5·4	1·6	0·5
Ophiuroidea	?	?	5·2	2·2	0·4
Asteroidea	33·3	?	9·3	3·7	1·2
Holothurioidea	22·7	?	12·3	8·4	2·8

These averages, obtained for all the oceans of the world are corroborated by the material collected from the Kuril Trench. An analogous decrease was observed ranging from 100 species at a depth of 1,000 m to 6 species at 9,700-9,950 m. This impoverishment of the bottom fauna of the Kuril Trench is illustrated by Fig. 4.

* After different data, published by XIV Intern. Zool. Congress.

A different regularity was established for the systematic groups of plankton animals investigated in this respect. Their diversity increases with depth, with a maximum in the abyssal zone. This was well demonstrated on copepods by BRODSKY (1952) (Table 5).

Similar data were obtained by BIRSTEIN and VINOGRADOV (1955) for pelagic gammarids (Table 6).

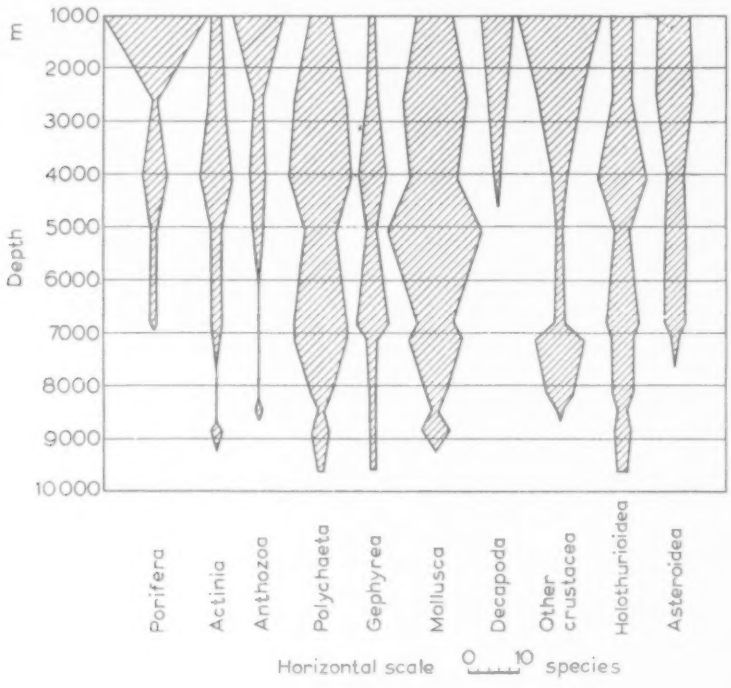

Fig. 4.

Table 5. Number of species of calanids per 1 m³ at different levels of the Kuril Trench (after BRODSKY, 1952).

Horizon (m)	0–25	25–50	50–100	100–200	200–500	500–1,000	1,000–4,000
Number of species	7	7	9	10	28	30	87

An increase in specific variety related to depth was observed also in chaetognaths, pelagic coelenterates, mysids, prawns and some others. However on the extreme limits of oceanic depths, in the ultra-abyssal zone, the specific variety of plankton shows an abrupt decrease, similar to that of the bottom fauna (Fig. 3).

Another very conspicuous dissimilarity observed in the reaction of benthos and plankton animals to increasing depth is their different colouring.

Strongly pigmented bottom organisms are prevalent at depths lesser than 1,000 m. But in the abyssal zone, and especially in the lower abyssal subzone, white and yellowish pigmentless organisms become predominant. On the contrary the plankton of the abyssal zone is characterised by a deep red colouring; and only representatives of the ultra-abyssal plankton (excepting the amphipod *Andaniexis subabyssi*) are all devoid of pigment.

The intense dark red colouring of abyssal plankton can be considered as a strong argument in favour of the existence of a powerful system of vertical migrations performed by these planktonic organisms. We know that traces of perceptible light penetrate in the water no deeper than for 1·5 km nevertheless red planktonic animals inhabit depths of 6-7 km. It seems quite possible that they ascend periodically to a zone where they become exposed to the action of light and are using the protective properties of their pigment. On the other hand, the unpigmented plankton of the ultra-abyssal zone is evidently fully isolated from the illuminated water-layers. Abyssal bottom animals do not perform vertical migrations nor do they develop protective pigments.

Of special interest are dissimilarities related to depth, observed in the feeding habits of bottom- and plankton animals.

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Table 6. Number of species of pelagic gammarids in different vertical zones of the Kuril Trench (after BIRSTEIN *and* VINOGRADOV, 1955).

Zone and subzone	*Number of species*
Surface	1
Transitional	1
Upper-abyssal	13
Lower-abyssal	12
Ultra-abyssal	6

Prior to the investigations carried out by the *Vitjaz* almost no attention was given to the feeding of deep-sea animals. Some scattered information is found in the literature on analyses of the gut contents of a leptostracan crustacean *Nebaliopsis typica* (Rowett 1943), three species of deep-water crabs (DOFLEIN, 1904) and soft sea-urchins Echinothuriidae (MORTENSEN, 1938); the gut of the latter contained, among other materials, remains of land and coastal vegetation.

SOKOLOVA (in press) has investigated in detail the content of the intestines of bottom animals; it was found that with increasing depth bottom-detritus-eaters gradually acquire a higher relative importance in the bottom fauna, whereas predators and suspension-feeders become less important. At the extreme depths investigated (9,800 m) all suspension-feeders disappear, as well as almost all carnivorous benthos-eaters, with the exception of polychaetes of the genus *Maccellicephala*; of the bottom-detritus-eaters only roughly sorting holothurians of the Elasipoda group and echiuroids are left.

As regards the plankton fauna, the investigations of TCHINDONOVA and VINOGRADOV (in press) have shown that in this case, on the contrary, the relative importance of predators greatly increases with increasing depth. It is only in the surface zone, at night, that pelagic animals utilise the abundant phytoplankton.

When these herbivorous forms return to greater depths they become the prey of numerous deep-water predators. Chaetognaths, pelagic prawns, amphipods and mysids, jellyfish and ctenophores feed on the plant-eaters, and furthermore devour one another. Among the many predators are forms able to use various kinds of food. Thus the mysid *Gnathophausia gigas* and the euphausiid *Bentheuphausia amblyops* attack live animals, eat their excrements and obtain food by means of filtration. On the other hand the leptostracan crustacean *Nebaliopsis typica*, which is provided with a pouch-like diverticulum of the middle-gut feeds exclusively on eggs of deep-sea animals (ROWETT, 1943) and is able to store a considerable supply of food in this intestinal pouch.

As was to be expected, all the deep-sea fishes investigated were found to be predators. Some of them are very selective in their diet. Thus, according to BIRSTEIN and VINOGRADOV (1955a) *Acrolepis* feeds mainly on luminescent animals.

Closely related to the study of the feeding of deep-sea animals is another extremely important, though little studied problem – that of the dynamics of organic matter at great oceanic depths. In approaching this problem we are first of all confronted with the question of the main sources of food supply.

KROGH (1934) suggested two possible sources of food for the abyssal fauna: (1) excrements and corpses of surface animals and (2) dissolved organic matter resulting from the biological activity and decay of surface animals, assimilated by hypothetical deep-water organisms, as yet unknown, which, in their turn, serve as food to deep-water animals. The first source seems improbable, taking into account the considerable rate of mineralisation of dying-off organisms and of their excrements, and the time they need to descend to the immense oceanic depths. The second assumption, not based on any facts as the author himself admits, remains a speculative hypothesis. Recently many investigators (EKMAN, 1953; YONGE, 1953; FAGE, 1953; ZOBELL, 1953) have emphasized the paramount importance of bacteria in the nutrition of deep-sea animals. According to ZOBELL (1953) heterotrophic bacteria are using dissolved and colloidally dispersed organic matter rather than the formed fragments of the inhabitants, of upper water layers. VINOGRADOV (1953, 1955) approaches the question from another standpoint – that of the probable importance of vertical migrations in transporting organic matter produced in the zone of photosynthesis down to the great oceanic depths.* The pelagic crustaceans feed at night at the surface and descend in the daytime to depths of 500 or even 800-1,000 m where they become the prey of the deep-water predators, the latter themselves being unable to ascend to the upper layers.

It may be assumed that when these predators return to their greater depths, they become in their turn the prey of the lower abyssal dwellers. Thus a ladder of migration is formed, by which organic matter produced in the upper layers is brought to the greatest depths of the ocean.

Notwithstanding all these data on the nutrition of deep-sea animals and its sources, the problem of the dynamics of organic matter is far from being solved. We cannot even say with certainty whether deep-sea animals live under conditions of acute food shortage, or whether they are supplied with food in sufficient quantities. In any case some of their food habits and processes of food digestion are very peculiar.

* The significance of vertical migrations in transference of food resources to deep depths is pointed out also by MARSHALL (1954) and GRAY (1956).

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Most striking in this respect are the data recently obtained by IVANOV (1955) on the total absence of an intestine in representatives of a most remarkable class of deep-sea animals, the Pogonophora. IVANOV has discovered on the cephalic tentacles of these animals, giant-cell pinnulae which are penetrated by blood vessels; he believes that the pogonophores digest their food externally by means of glandular cells set at the base of the pinnulae. The digested food is passed through the pinnulae into the circulatory system, and distributed through the whole body.

The question of the food supply of abyssal fauna is of great interest in relation to another remarkable peculiarity of deep-sea animals. A comparison of related species of the same genus, but inhabiting different depths, usually discloses a definite tendency to greater body-size with greater depth. This is observed both in bottom and in plankton animals, and seemingly does not depend on the character of food nor on the manner of feeding. This increase in body size can be illustrated by the example of *Amblyops* – one of the eurybathic genera of mysids: the largest of its species was collected by the *Vitjaz* from the greatest depth of the Kurile-Kamchatka trench (Table 7).

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Table 7. Depth of habitat and body-size of different species of the genus Amblyops.

Species	*Depth (m)*	*Length (mm)*
A. kempi Tattersall	700–1,463	16
A. tenuicauda Tattersall	820–1,400	17
A. abbreviata M. Sars	366–1,372	18
A. ohlini Tattersall	1,940–1,980	25
A. crozeti G. O. Sars	2,930	30
A. magna n. sp.	7,800	38

This increase in size with depth is even more strikingly expressed in species of the deep-water isopod *Haplomesus*. Two new species of this genus were discovered by the *Vitjaz* in the same trench.

Up to now six species of this genus had been known: five from the North Atlantic and one from the Polar Basin. The length of the Atlantic species found in depths ranging from 1,350 to 3,276 m varies from 2 to 4·5 mm and the arctic species taken at a depth of 698 m, has a length of 4·5 mm, in comparison the first of the two new species of *Haplomesus* discovered by the *Vitjaz*, from a depth of 8,000-8,200 m measured 14 mm, and the second, from 4,860 m – 7·5 mm.

An analogous increase in size is recorded for cirripeds of the genus *Scalpellum* and some other forms. Thus, for instance, the mysid *Eucopia australis*, characteristic of the lower abyssal subzone is considerably larger than *E. grimaldii* which lives in the upper abyssal subzone. It is interesting that the same tendency to an increase in body-size with transition to life in greater depths is manifest in the ontogeny of some deep-sea animals. Large mature, or nearly mature individuals of many pelagic animals, such as the mysid *Gnathophausai gigas*, the euphausiid *Bentheuphausia amblyops*, the leptostracan *Nebaliopsis typica* – inhabit greater depths than their smaller young stages.

Finally, attention has already been drawn to the giantism of the deep-water representatives of certain systematic groups. For example, there is the foraminiferan

Bathysiphon, common at great depths of the north-western Pacific, whose tubular shell reaches a length of 15 cm.

From this evidence, the question arises of the cause of this increase in size of many deep-sea animals with increasing depth of habitat.

The factor of temperature is obviously of no great importance, as no significant changes of temperature occur between depths of 2-5 km and 6-8 km. Neither can differences in food habits and quality of food affect the body-size of deep-sea organisms, considering that deep-water giantism is observed in forms having different food habits and using various kinds of food. The only conclusion possible is that there are some peculiarities in the metabolism of many deep-water organisms which determine this charactistic phenomenon of giantism.

There is yet another aspect to be considered of the marked changes undergone by deep-water fauna with increasing depth of habitat – namely the relationships of species inhabitating different depths. In the process of systematic analysis of the collections of the *Vitjaz* it becomes increasingly evident that the most ancient and primitive representatives of different groups of animals tend to concentrate in greater depths. Thus among isopods representatives of the most primitive suborder Asellota prevail; among mysids representatives of the most primitive family Lophogastridae and primitive tribe Erythropini; among decapods representatives of the almost extinct ancient family Eryonidae, the primitive family Oplophoridae, known as fossil from the Lower Cretaceous, occur; the stalked sea lilies, preserved from an even more remote past; the family Bonneliidae among the Echiuroidea; the family Aphroditidae among Polychaeta, etc.

Along with these ancient and primitive forms the abyssal fauna also comprise species with a younger phylogeny: such as some ophiuroids, starfishes and others.

Many investigators, especially SVEN EKMAN (EKMAN, 1953) have noticed this conservation of ancient groups and forms in the abyssal depths. This fact is of a great interest not only in itself but also in its bearing on the zoogeography of the ocean. Considering the predominance of ancient forms at greater oceanic depths we may surmise that a zoogeography of oceanic depths would differ from a zoogeography of the sublittoral region, and would reflect not so much the recent relations and hydrographical features of seas and oceans, as the corresponding characteristics of very ancient seas, where the primitive groups were formed, which at present inhabit the great oceanic depths.

There are facts showing evidence that deep-sea faunas on both sides of Central America differ in their composition, whereas the shallow-water faunas of the same parts of the ocean are very much alike. This may be explained by the fact that during the Mesozoic and Palaeozoic era, the shallow-water region existing in place of the isthmus of Panama, prevented an exchange of deep-water faunas between the Atlantic and Pacific Oceans. The dissimilar features of these two faunas seem to be of a more ancient origin than the similar features of shallow-water faunas.

It was also found that the waters beneath the mean depth of the Pacific, are inhabited by some scores of families, genera and species of benthic and planktonic animals, many of which never occur at lesser depths. A considerable part of these species proved to be new: furthermore some unknown taxonomic units of a higher rank were discovered. Thus there were several species of pogonophores, one new family of pelagic amphipods (Vitjazianidae), two ultra-abyssal genera of the family

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Bonneliidae (*Jakobia*, *Vitjazema* and *partim Alomasoma*) and others. It is possible that this fauna, isolated systematically from the neighbouring fauna of the lower abyssal subzone, was formed after the appearance of the greatest depths of the Kuril Trench, by a descent of the inhabitants of the lower abyssal to the extreme depths. It may be assumed that analogous ultra-abyssal faunas in other oceanic depressions were formed in a similar way. If this assumption proves to be true, the degree of isolation of the ultra-abyssal fauna in a depression from the fauna in the lower abyssal depths, can be used as an index of the chronology of its extreme depths. According to the geological data available the known oceanic depressions are of diverse ages, so that we may expect each of them to harbour a rather distinct ultra-abyssal fauna.

Due to the zoogeographical heterogeneity of the fauna at different depths the oceans of the world have to be divided into zoogeographical regions not as a whole but by separate vertical zones. This was made manifest during the systematic analysis of some animals from the Kuril Trench. Thus, pelagic gammarids from this trench could be divided, according to the character of their habitat, into five groups: Pan-oceanic, Atlanto-pacific, Arctic, North-pacific and Endemic species. It was found that the ratios of these groups change abruptly from one vertical zone to another (Table 8).

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Table 8. *Ratio of zoogeographic groups of pelagic gammarids in different vertical zones of Kuril Trench* (*percentage of species*) (*after* BIRSTEIN *and* VINOGRADOV, 1955).

	Pan-Oceanic	*Atlanto-Pacific*	*Arctic*	*North Pacific*	*Endemic*
Upper abyssal subzone	46·1	38·5	7·7	7·7	–
Lower abyssal subzone	8·3	33·3	–	8·3	50
Ultra-abyssal zone	–	–	–	–	100

There are reasons to assume that the connections between faunas of the Pacific and the Atlantic oceans, established for the upper and lower abyssal subzones, have been produced through different channels: mainly through the Polar Basin for the upper abyssal subzone, and through the Antarctic and Indian ocean – for the lower abyssal subzone.

Institute of Oceanology,
Academy of Sciences of the U.S.S.R.

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INSTRUMENTAL NOTE

A Bottom-Water Sampler

THE device described herein enables one to take water samples with one to six water bottles at predetermined depths from one to sixty metres from the bottom. It is essentially a Nansen bottle holder which trips the attached bottles at predetermined heights above the sea floor. These heights are measured from the bottom up instead of from the sea surface down as is common practice in taking water samples.

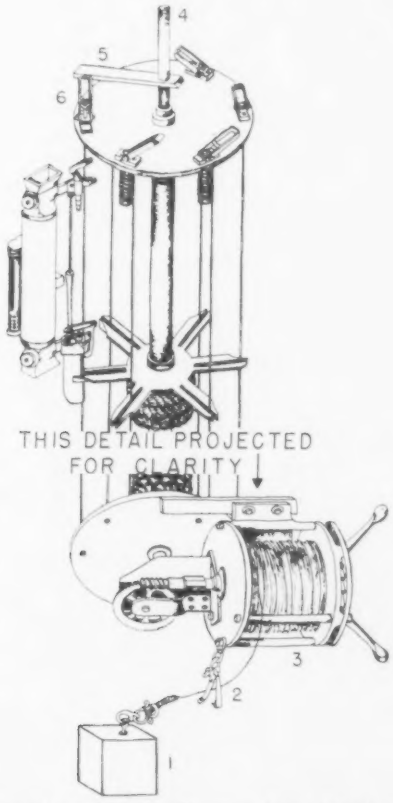

Fig. 1. Instrument viewed from above. Detail of bottom below lettering portion viewed from below.

The device consists of the following major parts shown in the accompanying sketch: (1) weight, (2) weight release, (3) wire storage spool, (4) central column, (5) tripping arms (five are used but only one is shown in Fig. 1), (6) spring-loaded plungers. Various enclosures are possible to protect the working parts and to facilitate handling on board ship. We used a regular tetrahedron, seven feet on each side, constructed of $\frac{1}{2}$ in. galvanised pipe. The bottle holder was mounted with its top at an apex; the opposite side of the tetrahedron served as the base.

The apparatus is lowered by a hydrographic winch to the sea bottom, and the sounding of an imploding glass ball is used to indicate the bottom rest position. At this point the weight (1) is automatically released, tripping the first bottle with a flexible wire lanyard. The hydrographic wire is retrieved slowly (at about 20 m./min.) unreeling the wire from the spool. The slow rotation of the arms trips the plungers in turn and hence the remaining bottles are released. After hauling in a length of hydrographic wire equal to the length of the wire on the spool the apparatus is retrieved at normal speed. The apparatus was used on *Atlantis* cruise A-213 in the vicinity of the Cariaco Trench. The following data from three lowerings indicate the attached thermometers reach equilibrium. It is important to note that time spent at each depth is probably not enough to assure equilibrium except in such cases as the Cariaco Trench where independent measurements show that the temperature gradient near the bottom is nearly adiabatic. The depths were (a) estimated from the corrected sonic depth and the positioning of the tripping arms and (b) determined with protected and unprotected deep-sea reversing thermometers.

Station			Estimated Depth	Thermometric Depth
5278	12°36′N 58°34′W	Bottom (sonic)	1852 m 1853 m	1856 m
5279	12°41′N 59°40′W		1111 m 1121 m 1166 m	1112 m 1116 m 1166 m
		Bottom (sonic)	1167 m	
5280	11°29′N 60°46′W		394 m 416 m 449 m	394 m 416 m 445 m
		Bottom (sonic)	450 m	

The agreements between the estimated and thermometric depths are all within the errors expected from our experience with the particular thermometer pairs used.

RICHARD S. EDWARDS
FRANCIS A. RICHARDS

Woods Hole Oceanographic Institution, Contribution No. 865

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LETTERS TO THE EDITORS

Importance of studies of the ocean depths

THE surface of the seas and oceans extends over 361,000,000 km^2 or 70·7% of the terrestrial globe. The total volume of this immense mass of salt water amounts to 137,000,000 km^3.

Eighty-eight and one tenth per cent of the total surface of the ocean (or 61·5% of the total earth's surface) covers depths greater than 1000 m. In the atmosphere the biosphere or living space extends vertically up to a hundred metres (with the exception of temporary sojourns of birds, insects, and some other organisms, as well as of their sporocysts, in higher layers). The oceanic part of the biosphere, populated from surface to bottom, has an average depth of 3800 m (accessory seas included). Consequently the living space of the deep-water zones of seas and oceans is at least 30-35 times as great as that of the atmosphere. Or, in other words, the deep region of the ocean is, spatially, the greatest existing biotope, immeasurably wider than all the other biotopes put together.

Until recently our knowledge of the depths of the world's oceans was very restricted. It was generally confined to data bearing on the distribution of depths and superficial layers of the sea floor, and on the hydrological, hydrochemical, and biological characteristics of the water masses, and their dynamics.

But studies of oceanic depths – bottom relief, bottom sediments, composition, and distribution of abyssal faunas – are meant to provide correct answers, to aid in elucidating many important problems of this history of the world's oceans, palaeogeography in general, geological chronology, geotectonics, history of development of marine faunas, palaeoclimatology and other associated fields of science. Our insufficient knowledge of the ocean depths has impeded the progress of many related disciplines.

During the last decade a growing interest in the study of the ocean depths has been observed in many countries. Within these years three around-the-world deep-sea expeditions have followed one another : the Swedish expedition on the *Albatross*, the Danish on the *Galathea*, and the British *Challenger II*.

For many years systematic research work has been carried on by American research vessels, notably by the *Albatross* and *Atlantis*. For seven years the *Vitjaz* has been carrying out complex oceanographic investigations of the deep-water zone in the Okhotsk, Bering, and Japan seas, and the adjacent part of the Pacific Ocean. ICSU established a special committee on deep-sea investigations and *Deep-Sea Research* was initiated four years ago as an associated periodical.

All these facts are evidence of the very great interest in deep-sea investigations which has grown up in recent years ; hitherto this branch of the science of the earth and its past, has been very backward.

What are the causes of this new interest ?

One of the most important problems of geology is the question of the antiquity of the oceans, the relative youth of the Atlantic and different parts of the world's oceans. Modern seismographic methods (perfected and refined) permit estimates of the total thickness of oceanic bottom sediments. If such a map could be obtained it would undoubtedly put an end to the long discussion on the relative antiquity of the oceans and their different parts. It would also be possible to reconstruct more reliably than before, the outlines of oceanic basins of past geological periods.

The determination of the thickness of bottom sediments underlying the water masses of the oceans will permit us to pose a question, which so far has not been approached. An accumulation of deposits during billions of years, even at an extremely slow rate of deposition (some few mm per 1,000 years), should assuredly raise the level of the world's oceans, such a rise being a matter of thousands, rather than of hundreds metres. Allowing for the moistness of bottom sediments (about 70%) and the presumed length of existence of the world ocean this rise of the ocean level may be assumed to reach 2-3 km, i.e. the whole horizon of the bathyal. Furthermore the rate of this process may have been far from uniform.

Apart from this, the study of deep-sea depressions (more than 7000 m deep) is of great interest, though their total area covers merely 0·1 % of the whole area of the ocean. These depressions conceal some of the most important elements of the geotectonic relief of the earth's crust. They are, together with the adjoining island arcs, geosynclines in their early phases of formation and are accompanied by a complex of characteristic phenomena, including earthquakes and volcanic activity. The deep-sea depressions attract the attention of investigators by their structure, geographical distribution, and fauna. There are nineteen such depressions in the world ocean, and the far greater majority of them (15) are situated in the Pacific ocean. The deep-water depressions, extending over many thousand miles on the western side of the Pacific, from the Aleutian to the Philippine and Indonesian islands, follow the great line of rupture of the earth's crust, along the so-called andesite line, where the sial shell of the continent joins the sima shell of the floor of the Pacific.

The Kuril Trench, which lies to the east of the Kuril island arc, is one of the deepest of the Pacific depressions (10382 m) and nearly the youngest of them at that. Here are well expressed all the elements of an island arc, such as a deep-water marine basin (Sea of Okhotsk) adjoining it from the side of the continent, and a depression from the side of the ocean. The great importance of studies of the island arcs, as an early phase of geotectonic processes, has been repeatedly stressed by Academician A. N. ZAVARITZKY, who believes studies of the Pacific ocean, with the widest possible scope, to be " one of the most important problems that confront the science of the earth " and considers the problem of island arcs its most fundamental part. " No insight," says ZAVARITZKY " can be obtained into the formation of the earth's surface in general, its continents, and its seas . . . without elucidating the question of the origin of the Pacific ocean . . . and to this problem are in their turn closely related . . . a whole chain of the deepest and basic questions of geophysics, geology, cosmogony . . . " " The tasks confronting the sciences of the earth's pertinent to the study of the margins of the Pacific ocean, are indeed unlimited "*.

This appreciation of the problem given by ZAVARITZKY from a purely geological position, cannot be underrated; on the contrary it could be greatly stressed and developed from the standpoint of many related sciences, such as palaeogeography, palaeoclimatology, biochemistry, biology, etc.

Studies of the great depths of the far-eastern seas and adjacent parts of the Pacific were initiated in the U.S.S.R. in 1932 by Professor K. M. DERJUGIN, but these investigations were confined to depths of some 4000-4300 m. In 1949 the R/V *Vitjaz* of the Institute of Oceanology of the Academy of Sciences of the U.S.S.R. started its investigations involving the vast regions of the north western part of the Pacific ocean and all the depths. Extensive material was collected by the *Vitjaz* on the Kuril Trench, as well as on the Aleutian, Japan, and Bonin trenches.

A comparison of the deep-sea depressions on the western side of the Pacific reveals a similarity of depth between the deepest of them, the depths ranging from 10300 to 10800 m. There is also a striking resemblance of the configuration of the depressions and their profiles. Their lateral slopes are very steep, whereas the bottom proves to be utterly flat. These similar features seem to imply the existence of some definite structural feature in the surface layer of the earth's crust underlying the oceans, which accounts for this likeness.

The narrowness of the Kuril Trench is one of the most characteristic features of its bottom relief. The trench outlined by the 9000 m isobath has a length of 550 km by a width of 5 km. The 6500-m isobath connects three depressions – the Kuril, the Japan, and the Bonin. To the south of the latter the floor of the ocean rises considerably. The isobath of 5000 m links these three depressions to the northwestern part of the Aleutian Trench. The northern part of the Kuril Trench is characterized by an extensive development of tectonic forms of relief. Faults, slides, and denudations of ancient bedrocks often present a very variegated picture. Another noteworthy feature of the macrorelief of the Pacific ocean floor is a meridionally directed elevation in its northern part. This elevation divides the depths of the ocean into an eastern and a western basin. It is especially well expressed in the region of the Hawaiian islands and northwards up to the Aleutians. It can be also traced southwards down to the Antarctic. However it will be the task of future investigations to determine its extent and character for the whole Pacific ocean and to attempt to draw an analogy with the meridional underwater elevation of the Atlantic.

Many sedimentary rocks on the land were formed on the bottom of oceans and seas, but very little is known about how they are formed at present. We can merely state that the formation is controlled chemically, physically, biologically, and geologically by the overlying thickness of oceanic waters.

*Zavaritzky A. N. (1952) *Ostrovniye dugi*, *Moscow* (in Russian).

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Cores several meters long have already been obtained (the *Vitjaz* has taken cores of 34 m), and cores of 100 and 150 m will probably be obtained in the near future. This will permit an insight into the processes of diagenesis, i.e. the transformation of marine sediments into sedimentary rocks in the course of many millions of years.

A comparison of the results of stratigraphic and biologic analyses (especially for diatoms and foraminifera) by the method of carbon-isotope and analogous techniques allows very precise assessment of the climatic variations of the Glacial and Post-Glacial period. It is hardly possible to overrate the possibility of palaeoclimatologic reconstructions for many million years, for the whole terrestrial globe.

It seems quite probable that it will be possible to reconstruct the chronology of palaeontologic time for even greater periods. Oceanic bottom sediments in most cases preserve their regular stratification a condition which together with a considerable moistness, facilitate a most thorough analysis. It may be reasonably assumed that sediment solutions preserve some chemical characteristics from the time of their deposition. If so it will be possible to reconstruct the salinity of seas and oceans for the geological time corresponding to the length of the core obtained. The history of the salinity of the world's oceans still remains one of the most enigmatic problems of oceanology.

Many problems are hidden too in the dynamics and chemistry of the oceanic bottom-water layers. Data so far available seem to indicate a rather uniform saline, gaseous, and even thermal regime of the ocean depths. Thus in the immense expanse bounded by the 40° parallels the temperature of the bottom waters varies between 1-2°C, salinity within 34·8-34·9‰. The oxygen content is about 5 ml/l and the active reaction varies from 8·0 to 8·1. We might infer an extreme uniformity of the deep water in respect of all major indices. But is it really so ? Do our scales of uniformity and our methods of physical and chemical analyses used in oceanography, apply to this case ? We know that the deep-sea red clay is very rich in radium. Holothurians of the elasipodid group, echiuroids, pogonophores, siliceous sponges, and other forms that predominate in the deep-water fauna, are characterized by a peculiar chemical composition. Are there some peculiar biochemical provinces in the deep-water zones which determine to a considerable degree the distribution of organisms? Do the deep-water organisms, which exist with seemingly very small differences of environmental factors, possess a special sensitivity to the smallest variations, not detected by our methods of analysis ? Thus the fauna may be used as a very fine indicator of the homogeneity (or heterogeneity) of environmental factors in the deep-water zones of the ocean.

Investigations of the deep-sea fauna, including that of the ultra-abyssal (beyond depths of 6000-7000 m) carried out during the last few years have proved the incorrectness of our notion of a geographical and vertical homogeneity of the pelagic and benthic deep-sea fauna. On the contrary it can be divided vertically, into well-defined zones. The resemblance between the deep-sea fauna of the Pacific, Indian, and Atlantic ocean, their southern and northern parts, their eastern and western depressions (where delimited by meridional elevations) is very relative and insignificant. Furthermore different groups of deep-water fauna endemic to one or another part of the world ocean are often groups of a high taxonomic order. The vertical and horizontal dissimilarity in the distribution of deep-sea fauna, persisting through periods of geologic time, cannot be explained by impediments in the dispersion of populations. The cause must be sought also in a heterogeneity of their environment despite its apparent homogeneity. Some peculiarities of different regions of the sea bottom, particularly the chemical ones, may still remain unknown. Microvariations of chemical and physical factors of the deep water layers that cannot be precisely determined by our analytical instruments and methods are perceptible to the deep-water organisms which have adapted themselves precisely to these peculiar conditions of life.

It is also probable that the dynamics of those layers of oceanic waters which are deepest and nearest to the bottom, are still hidden from the investigators. The relief of the sea floor affects considerably the circulation of the water mass adjacent to the bottom, controlling the system of currents and cyclonic and anticyclonic circulations, of perhaps no lesser complexity than that of the surface layers.

The historical aspect must evidently also be taken into consideration. The geographical distribution of the fauna of the upper layers of the oceans reflects generally the present orography of seas and oceans or that of the nearest geological periods the Post-Glacial, Glacial, and –, to a lesser degree –, the Tertiary.

Not a few data are now available which suggest that at great ocean depths the geographic distribution of fauna may still bear the imprint of former geological periods with a different orography of oceans. The deeper the horizon the more ancient is the orography of the oceans where the causes of the peculiarities of the recent distribution are to be sought,

A detailed discussion of several problems pertinent to the study of the deep-sea fauna is given in another paper which will be published in this journal.

The author could not approach many questions of no lesser interest than those discussed in this paper. There are undoubtedly many problems of equal importance in the domain of physical and chemical oceanography, which also require a thorough discussion.

L. A. ZENKEVICH

Institute of Oceanology
Academy of Sciences of U.S.S.R.

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"Oceanology" versus "Oceanography"

THE discussion aroused in *Deep-Sea Research* concerning the terms oceanology and oceanography is of fundamental interest. It has become desirable to attain some agreed point of view and avoid confusing these two terms. There is no doubt as to this confusion. In 1931 there appeared a fine book written by the well-known American sea biologist H. B. BIGELOW. He called the book *Oceanography*, and it included physics, chemistry, geology, and biology. BIGELOW concluded his book with an interesting chapter (VII) named "Physical, chemical, geological, and biologic unity in the sea." In other words, H. BIGELOW together with many others attaches to the term oceanography a sense which includes our whole sea knowledge and all aspects of these sciences. The sixth chapter of this book is named "Economic value of oceanographic investigations." The author of the well-known book *International Aspects of Oceanography*, I. W. VAUGHAN (1937), evidently treats the term in the same way. On the other hand, many authors do not understand by the term "oceanography," the whole of sea science but only a part, and primarily without biology. So, for instance, there appeared in 1955 a fine book *Papers in Marine Biology and Oceanography* dedicated to BIGELOW, the heading of which separates sea biology from oceanography. I fully subscribe to the opinion of BIGELOW (1931) about the unity of processes, performed in the ocean, and this ought to be reflected in the name of the science studying the ocean in this unity (physical, chemical, geological, and biological).

But there arises a second question – what will be the name of this science? Shall we use the old term, oceanography, or the new one, coming into broad use, oceanology? It seems to me that it is not worth violating the term oceanography since there are many people who understand in it primarily physical oceanography the bottom relief and sediments – and think frankly that biology is not a part and parcel of oceanography. On the other hand the term oceanology is very convenient in linguistics and nobody will have any doubt that it embraces all the science divisions of the sea hydrosphere (halosphere).

Thus, I think (together with Dr. BRUUN and Commander HALL) that the term oceanology has all the rights of citizenship. If the term oceanography appears to be more suitable to someone in the sense in which we use the term oceanology we may express a wish to indicate the sense in which it is used.

L. ZENKEVICH

Institute of Oceanology
Academy of Sciences of U.S.S.R.

The meaning of Strontium-calcium ratios

(*Received* 18 *July* 1956)

THOMPSON and CHOW (1955) have presented data on the strontium-calcium ratios for an array of objects – mostly the hard parts of marine invertebrate animals – that far exceed the total of all similar data previously available. The constancy of strontium-calcium ratios within similar types of organisms is stressed. This may be justified when compared with the ratios found among species from widely separated taxonomic groups living in the same habitat, but it appears that the differences found between closely related species, and even between different specimens of the same species, may be both real and significant.

Within any given species real differences must be attributable to environmental differences, functional differences, or both. If these factors can be determined, one more step toward understanding the processes determining the ratio of strontium to calcium in marine organisms may be made. Having collected some of the animals analysed, I should like to say that the following bits of evidence suggest that there may be an inverse relationship between growth rate and strontium-calcium ratio in bivalve molluscs:

1. The two specimens of *Modiolus modiolus* having the atom ratios (Sr/Ca × 1,000) of 1·37 were thin-shelled individuals, whereas the two having ratios of 1·52 and 1·60 were thick-shelled.

2. The *Mytilus edulis* with the 1·33 ratio was a thin-shelled individual, whereas the specimen with the ratio of 2·16 was heavy-shelled.

3. The three west-coast specimens of *Mya arenaria* were taken from a series previously studied (SWAN, 1952a). The specimen from Oregon with a ratio of 2·12 was from the Siuslaw River where shells are very thin. The shell from Washington with a ratio of 2·81 was from Garrison Bay where shells are thick, and the one with a ratio of 2·16 was from Argyle Lagoon and of intermediate thickness. Again, the light-weight shells have lower Sr/Ca ratios than the heavier shells.

The literature indicates that for several species of bivalve molluscs, heavy shells are characteristic of slow-growing individuals whereas lighter shells develop on rapidly growing specimens (FOX and COE, 1943, p. 215; BELDING, 1916, p. 149; EDMONDSON, 1922; SWAN, 1952b).

Thus, it is suggested that differences in the growth rate and environnment may be important in the determination of the strontium-calcium ratio in bivalve-mollusc shells.

Department of Zoology, University of New Hampshire, EMERY F. SWAN
and
Museum of Comparative Zoology, Harvard University.

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BOOK REVIEW

H. W. HARVEY: **The Chemistry and Fertility of Sea Waters.** Cambridge University Press, 1955. viii + 224 pages. 65 figs., 28 tables. 30s.

CHEMISTRY in its relation to oceanography or the marine sciences has lately been turning its interest toward general geochemical problems. The study of the marine hydrosphere is certainly a challenge to the best efforts of geochemists. Until now, however, the function of the chemist in the field of oceanography has been chiefly to serve the interests and purposes of biology. His principal task has been to investigate the chemical conditions of life in the sea and to explain why some areas of it are fertile and others barren. No one has contributed more to this end than has the author of this book, which, although with a different title, is really a revision and modernization of two earlier works on essentially the same subject. It is divided into two distinct sections: Part I, The Environment of the Flora and Fauna, and Part II, The Chemistry of Sea Water. The first of these is a summary of our present knowledge of the fertility of the sea, particularly as it is affected by changes in the chemical composition of the water.

The total life cycle is fundamentally the same in the ocean as in the terrestrial world. Photosynthesis, quantitatively as intensive, acre for acre in the sea surface as on the land, produces plants, which are thereupon " grazed " by herviborous animals, who in turn are eaten by voracious carnivores, and all eventually die and are decomposed by bacteria. Such biochemical factors as fertilizers, micronutrients, auxins and other growth-promoting substances, vitamins, enzymes, and substances involved in the respiratory processes – all are found in the sea. The sea-going agricultural chemist can find as much to keep him busy as can his landlubber brother.

Part II is a rapid summary of the chemistry of the major and minor constituents of sea water, and some discussion particularly of their biochemical significance. The chapter on the carbon dioxide system is a particular highlight, for this is a field in which the author has taken an active part. A brief chapter on analytical techniques is followed by an extensive bibliography.

The author may perhaps be criticized for his general disregard of the work of the Russians and the Japanese, which has been extensive. Also, he too frequently raises questions without going further, thus leaving the reader to flounder. Nevertheless, the book should be required reading for all " chemical oceanographers " and at least highly recommended to biochemists.

NORRIS W. RAKESTRAW

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Light generation in a sonic-scattering layer

ELIZABETH M. KAMPA and BRIAN P. BODEN

Abstract—1. Luminescence at the depth of the sonic-scattering layer in the San Diego Trough has been recorded at various times of day and night with a telerecording bathyphotometer. The mean intensity of the luminescent flashes recorded is remarkably constant at a value near $1{\cdot}1 \times 10^{-4}$ microwatts per square centimetre throughout the diurnal cycle. The mean frequency of flashes varies widely, being least (10 to 24 per minute) at midday, greatest (42 per minute) during the twilight migration of the sonic-scattering layer, and at an intermediate level (32 per minute) during the night.

2. The colour of the luminescence from the sonic-scattering layer has been determined by using interference filters with the photometer. The independence of the light generated at depth from that incident on the sea surface has been established by a comparison of the colours of the two. The luminescence from the scattering layer is blue-green; the emission is maximal near 478 mμ.

3. Laboratory determinations have been made of the intensity and spectral distribution of the luminescence of two species, *Euphausia pacifica* and *Pyrosoma atlantica*, present in the water on the night when scattering-layer luminescence was measured. The emission spectra of both forms are bimodal. The primary peak of *Euphausia pacifica* luminescence is at about 476 mμ, and the secondary is near 520 mμ. The primary peak of *Pyrosoma atlantica* luminescence is near 482 mμ, and the secondary is near 525 mμ. The intensities of luminescence of both organisms are compatible with the range of intensities encountered in the measurements of light generated in the sonic-scattering layer.

4. The problems presented to the oceanographer and the biologist by the introduction of bioluminescence records are discussed, and the situation of *Euphausia pacifica* in particular is considered. The depth distribution of this euphausiid in the San Diego Trough is thought to be photoregulated and associated with the 1×10^{-4} microwatt per square centimetre isolume. At the same time the animal is apparently stimulating itself at intervals with light of a colour to which it should, by virtue of its photosensitive eye pigment, be most sensitive. The intensity of this intermittent stimulation is ten to one hundred times that of the constant environmental illumination with which *Euphausia pacifica* is oriented throughout the diurnal cycle.

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THE generation of light *in situ* at various depths has been reported from the Atlantic Ocean by CLARKE and WERTHEIM (1956) and from the Pacific by BODEN and KAMPA (in press). In both oceans the light has been detected with underwater photometers which employ multiplier phototubes as sensors and which record continuously on electric recorders. The light is intermittent, and the intensity of the flashes is frequently as much as 1,000 times that of the background illumination. In some instances we have found that the frequency and intensity of the flashes are so great that the overall level of illumination actually increases, rather than decreases, with depth.

Luminescence is a common characteristic of the marine fauna (SVERDRUP, JOHNSON and FLEMING, 1942) and it has been suggested that this light in both oceans is of biological origin. This suggestion has been supported by our observation that there is a zone in which light increases with depth which corresponds with the depth of the sonic-scattering layer (DSL) in the San Diego Trough during the twilight migrations of the layer. JOHNSON (1948) and BODEN (1950) have demonstrated that this layer is associated with concentrations of plankton.

During the spring and summer of 1956 we have carried out a number of experiments,

at sea and in the laboratory, in an attempt to determine (1) whether the degree of bioluminescent activity in the sonic-scattering layer varies diurnally, (2) the spectral character of the light produced, and (3) what species may be responsible for the phenomenon.

The characteristics of the photometer used in the work both at sea and in the laboratory have been described by SNODGRASS *et al.* (in press). A three-position strip shutter has been installed in the instrument immediately in front of the photocathode. The first shutter position obscures the cathode entirely, allowing us to observe the instrument's dark current at regular intervals. The second position is a pinhole, the geometry of which is such that the light admitted is 1/1,000 of the light admitted when the shutter is in the third, or " open " position. The shutter position is adjustable by the operator on deck. This mechanism has increased the useful intensity range of the instrument from 7 to 10 log cycles, and it is possible to measure light intensity from just beneath the surface to depths of several hundred metres.

Interference filters are placed in the light path when colour measurements are to be made, and a collimating tube restricts the angle of acceptance by the photocathode to the useful 5° cone of the filters. The integrating disc of opal plastic at the outer surface of the optical system has the characteristics of a true Lambert collector, that is, under a uniform sky the intensity I_θ, collected from the direction θ, is determined by

$$I_\theta = I_0 \cos \theta \qquad (1),$$

and the instrument measures irradiance.

Irradiance, H, is calculated from

$$n = kH = \int_0^\infty ETSd\lambda \qquad (2),$$

where n = recorder reading in millivolts, E = energy of the source, T = transmission of the interference filter, and S = relative spectral sensitivity of the photomultiplier through the wave-length interval $d\lambda$. The value of k was obtained by calibrating the entire instrument against a Bureau of Standards source.

The time constant of the photometer is established by the rate of response of the electric recorder, and the limitations imposed by it will be considered in the discussions of individual sets of results.

As has been pointed out before, this instrument is equipped with a pressure-sensitive element, and the depths mentioned here were determined directly, rather than by calculation.

The observations and collections on which this report is based were made at intervals between 18 January and 9 August 1956 in the San Diego Trough (Lat. 32°40′N., Long. 117°40′W.).

Experiment 1. During the daylight hours on 20 February, the photometer was lowered repeatedly with the sensor oriented upward. In the majority of these casts interference filters were used, and the results will be discussed elsewhere. At midday, however, total irradiance was measured by sending the instrument down without filters. Discrete flashes of light were detected at a depth corresponding to the depth at which sonic scattering was recorded by the EDO echo-sounder (Fig. 1). These burst were sufficiently separate in time that they appear as individual spikes.

An hour before sunset the photometer, without filters and with the sensor looking upward, was lowered to 200 metres. It was maintained at this depth for two hours. Portions of the record obtained are shown in Fig. 2. The smooth slope of the first (right side) section of the record is typical of what

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had gone before. As the sun approached the horizon the light intensity detected at 200 metres decreased regularly. During this time the scattering layer had risen from 260 to 225 metres, and at 1806 hours its depth on the fathogram was 200 metres. Concurrently, the photometer began to detect frequent flashes, and these persisted until the instrument was finally brought to the surface at 1855 hours.

Total irradiance was measured at 0430 hours (three hours after moonset and two hours before sunrise) and again at sunrise (0630 hours) on the following morning.

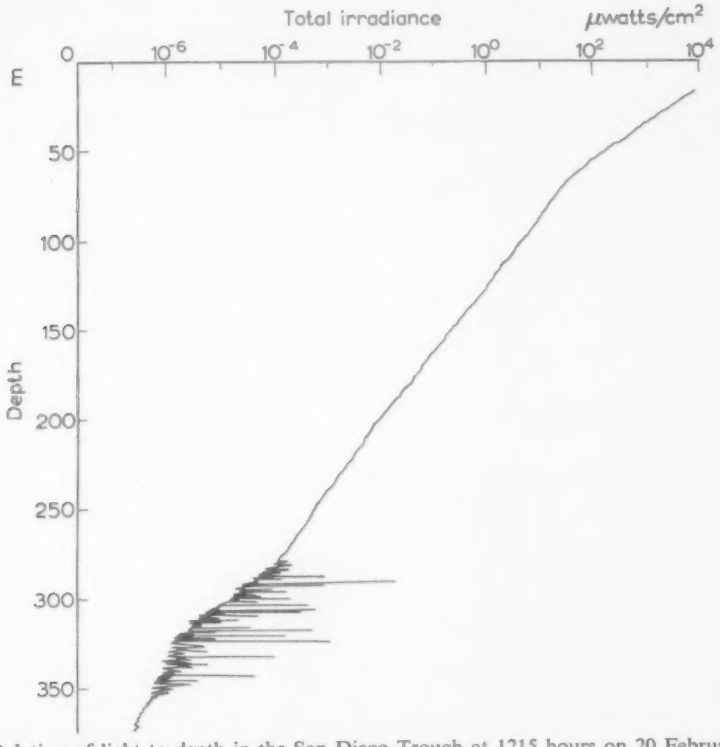

Fig. 1. Relation of light to depth in the San Diego Trough at 1215 hours on 20 February, 1956, obtained by applying equation (2).

Experiment 2. On 9 August records of luminescence were obtained from sonic-scattering layer depths at intervals throughout most of a 24-hour period. The photometer was lowered with its sensor oriented downward in order to reduce the masking of luminescent flashes by transmitted sunlight. On seven casts, the photometer was first lowered quickly to 100 metres below the sonic-scattering layer and then returned to the level of the layer and held at constant depth for several minutes.

DIURNAL VARIATION OF BIOLUMINESCENT ACTIVITY IN A SONIC-SCATTERING LAYER

A change in degree of any of the characteristics of luminescence – intensity and frequency of flashes are considered here – is indicative of a change in the degree of luminescent activity. The data at present at our disposal have been examined for evidence of any such change.

The findings, insofar as flash intensity is concerned, would lead us to believe that the animals in the sonic-scattering layer luminesce uniformly throughout the diurnal

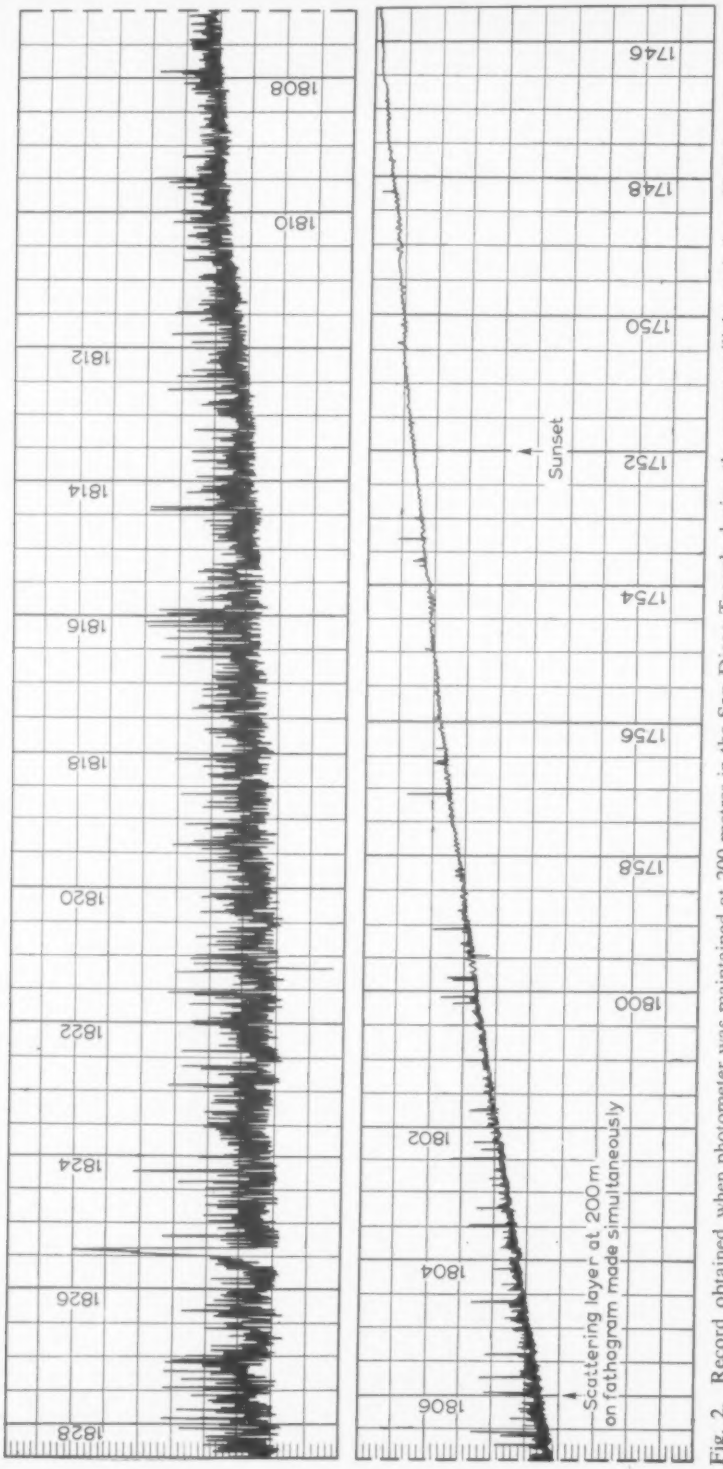

Fig. 2. Record obtained when photometer was maintained at 200 metres in the San Diego Trough during the sunset-twilight period on 20 February, 1956, showing the gradual reduction in the intensity of transmitted sunlight (upper right). The sonic-scattering layer reached 200 metres at 1806 hours, and luminescent from the layer may be seen.

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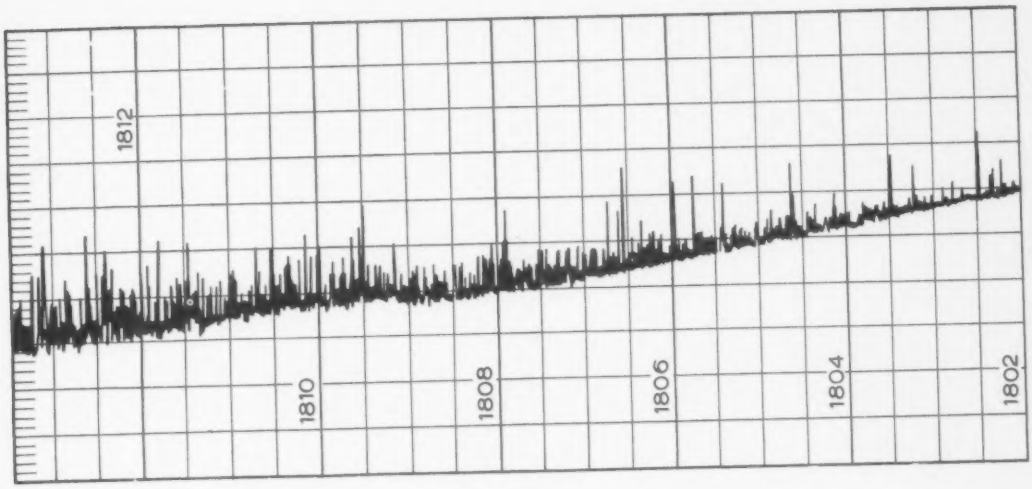

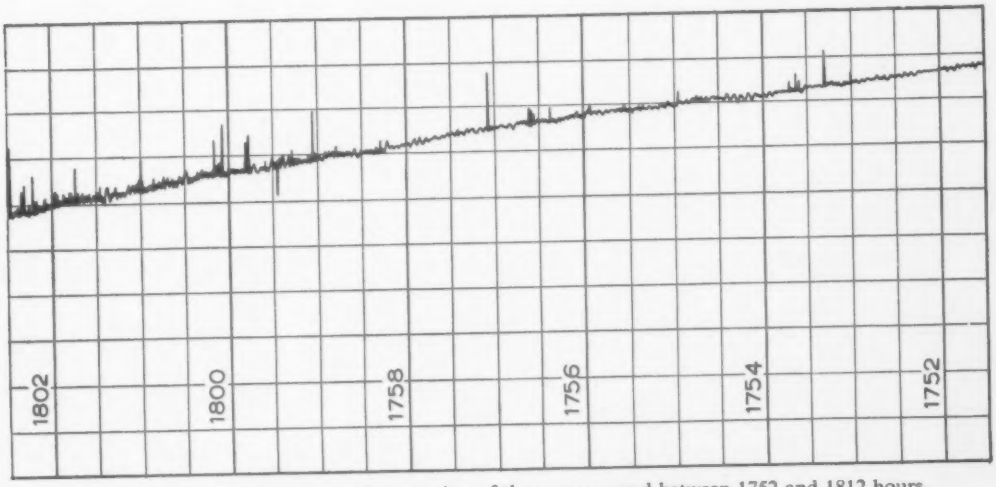

Fig. 2 *continued.* Enlargement of the section of the upper record between 1752 and 1812 hours.

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cycle. Values of total irradiance indicated by the heights of individual spikes have been tabulated from records for various times of day and night, and, although a considerable varibaility is exhibited by each of the individual records, no significant difference has been found either in the range of intensities detected or in the mean intensity throughout a diurnal cycle.

The results obtained from analysis of the 20-21 February records are typical and show the following:

DSL Depth (*metres*)	*Time* (*hours*)	*Range of flash intensities* (μ *watts/cm*^{2})	*Mean flash intensity* (μ *watts/cm*^{2})
300	1215	1×10^{-6} to $1{\cdot}5 \times 10^{-2}$	$1{\cdot}1 \times 10^{-4}$
200	1800	2×10^{-5} to $2{\cdot}5 \times 10^{-2}$	$1{\cdot}1 \times 10^{-4}$
30	0230	$1{\cdot}3 \times 10^{-5}$ to 7×10^{-3}	$1{\cdot}1 \times 10^{-4}$

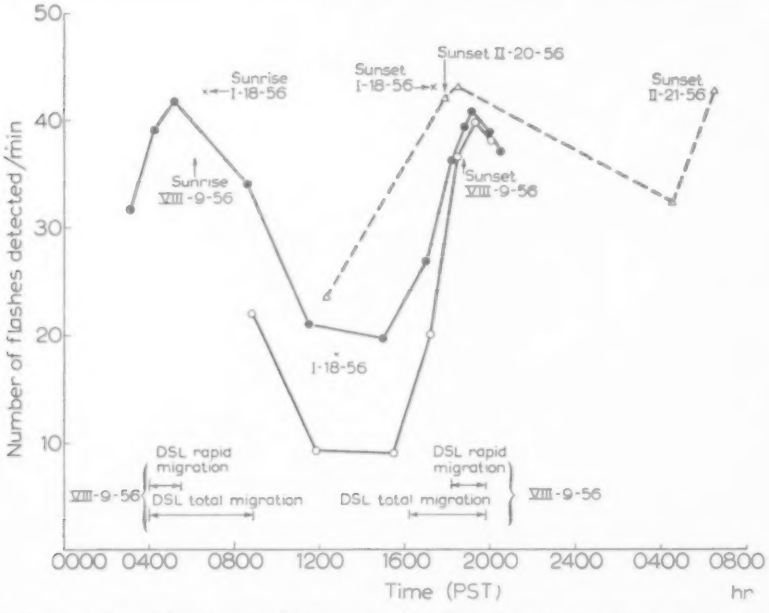

Fig. 3. Frequencies of luminescent flashes recorded at sonic-scattering layer depths at various times of day in January (×), February (Δ), and August (● and O), 1956. The closed-circle values for August were recorded while the photometer moved at 35 metres per minute; the open circles when the photometer was held at constant depth for several minutes. Periods of scattering-layer (DSL) migration are indicated for August.

The frequency of the flashes detected, on the other hand, differs greatly with time of day (Fig. 3). In every set of observations so far, the number of flashes recorded per minute from a sonic-scattering layer is least near midday. This frequency (Fig. 3) has been approximately 20 flashes per minute in three sets of observations taken in three different months with the photometer moving rapidly (30 to 40 metres per minute) through the layer. During the periods of vertical migration of the layer,

the number of flashes perceived by the photometer was about twice that recorded at midday.

When the photometer is held at a constant depth, the difference between the flash frequency at midday and that during the twilight migration is even greater. Although the number of bursts recorded with this procedure at twilight was not significantly lower than that detected by a rapidly moving photometer, the mean number (10 per minute) observed at midday with the photometer held as still as possible was about half that recorded when the photometer moved quickly through the layer.

The frequency of flashes increases gradually during the afternoon, and this increase appears to be associated with the onset of the scattering layer's migration. In this period the upward movement of the layer is slow but steady, and it is not until shortly before sunset that the animals attain their maximum upward velocity (KAMPA and BODEN, 1954). Concurrently, the frequency of luminescent flashes rises sharply, and a maximum number per minute may be observed in the hour after sunset. At the end of twilight, the upward migration has been completed. At about this time, the frequency of the luminescent flashes is diminished.

Because of technical difficulties the night-time relationship between sonic-scattering layers and luminescence is less readily established than are the daytime and twilight correlations. At the end of the evening migration, the trace of the scattering layer is frequently lost, either because the animals disperse to different depths in the water column and are perhaps no longer sufficiently concentrated to scatter sound, or because the layer has come so near the surface that its trace is obscured by that of the outgoing signal from the echo-sounder. Although luminescence – and most often luminescent strata – have been observed in the water column on every night when light measurements have been attempted, it cannot be said that these are related to sonic-scattering layers when no trace is distinguishable on the fathogram.

The most clear-cut evidence for a correlation between sonic scattering and luminescence during the middle of the night was obtained on 20 February. On that night both a scattering layer and a distinct luminescent stratum were present at about 30 metres. The mean frequency of flashes detected by the photometer was 32 per minute, a value midway between the minimum mean frequency (23 per minute) and the maximum mean (42 per minute) recorded from the same scattering layer at noon and at sunrise respectively on the following day.

Before even tentative conclusions can be drawn from these results, the limitations imposed by the methods and instruments used must be considered.

The importance of the procedure selected for gathering information to the interpretation of flash-frequency data has been stressed already. At the times when the degree of light generation in the sonic-scattering layer is high, as it is during the twilight migrations, the effect of the additional stimulus provided by dragging the 100-pound instrument with its attendant bridle and cable through the water at high speed seems negligible. When luminescent activity is lower, however, the method by which data are obtained becomes critical. Inasmuch as the photometer can never be entirely still, even when it is held at " constant " depth, we feel that the minimum frequencies are probably fallaciously high, and that nomral, spontaneous luminescence at scattering-layer depths at midday may be very slight indeed.

The time constant of the photometer, as it has been used so far, is established by the rate of response of the electric recorder. The limit of this response (about

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50 distinct ½-inch cycles per minute) is approached in the records of flashes from the migrating sonic-scattering layer. At twilight the actual number of flashes per minute could well exceed the number detected. Even at midday, the number of spikes on the record may still be less than the true number of bursts of light to which the instrument is exposed, for, from what is known of luminescence in other organisms, the duration of an individual flash would be of the order of fractions of seconds rather than fractions of minutes. It is probable, therefore, that the " flashes " of which we are speaking here represent integrals of a number of flashes rather than individual bursts.

Estimates of flash intensity are without doubt similarly distorted by the time limitations of the photometer. Examination of the data at hand might lead us to believe that we are dealing with an " all or none " phenomenon in scattering-layer luminescence, for the mean intensity of the flashes detected remains constant throughout the day. The range of variation in a single set of observations could be explained on the basis of the inverse square law, and it could be said that if the photometer were equidistant from every flashing organism, every spike would be of the same height.

Individual flashes, by virtue of their short duration however, may more often than not reach a maximum intensity and then decay before the instrument can respond. The effect of this time limitation on the record becomes greater as the level of the background light decreases. It is probable, therefore, that the true intensity of the light generated at depth is best represented by the intensities calculated for flashes superimposed on high levels of background light. A definitive statement of the possible diurnal variation in intensity of the luminescent flashes must await the impending development of faster photometric techniques.

Diurnal fluctuations in the amount of light generated at the depth of the sonic-scattering layer in the San Diego Trough are evidenced, despite the limitations of the system, by the data presented here on the numbers of flashes that can be detected at the level of the layer at various times of day and night. A photosensor, placed in the layer, detects at least twice as many flashes of light during the twilight periods as it does at midday, and the temporal limits of the periods of greater light production seem to be associated with the beginnings and ends of the vertical migrations of the layer (Fig. 3).

From the biological standpoint, interpretation of this correlation of migration with light generation may proceed along any one of several lines. First, it can be assumed that, in order to produce a continuous trace on the fathogram, organisms must be present in some minimal concentration such that their numbers per unit area, if not their individual acoustic cross-sections, permit them to reflect sound. From this assumption one can continue to two alternatives, either that the concentration of the organisms remains fairly constant throughout the day, or that the concentration varies widely but is always great enough to permit sonic scattering.

The first of these alternatives would require a two- to four-fold increase in the average bioluminescent activity of individual planktonts during the twilight migratory periods to explain the observed changes in the frequency of flashes. The second alternative allows the argument that at midday the animals are dispersed, and consequently the flashes detected per minute are few, whereas at twilight the animals are packed more closely together, and the greater frequency of flashing is indicative of

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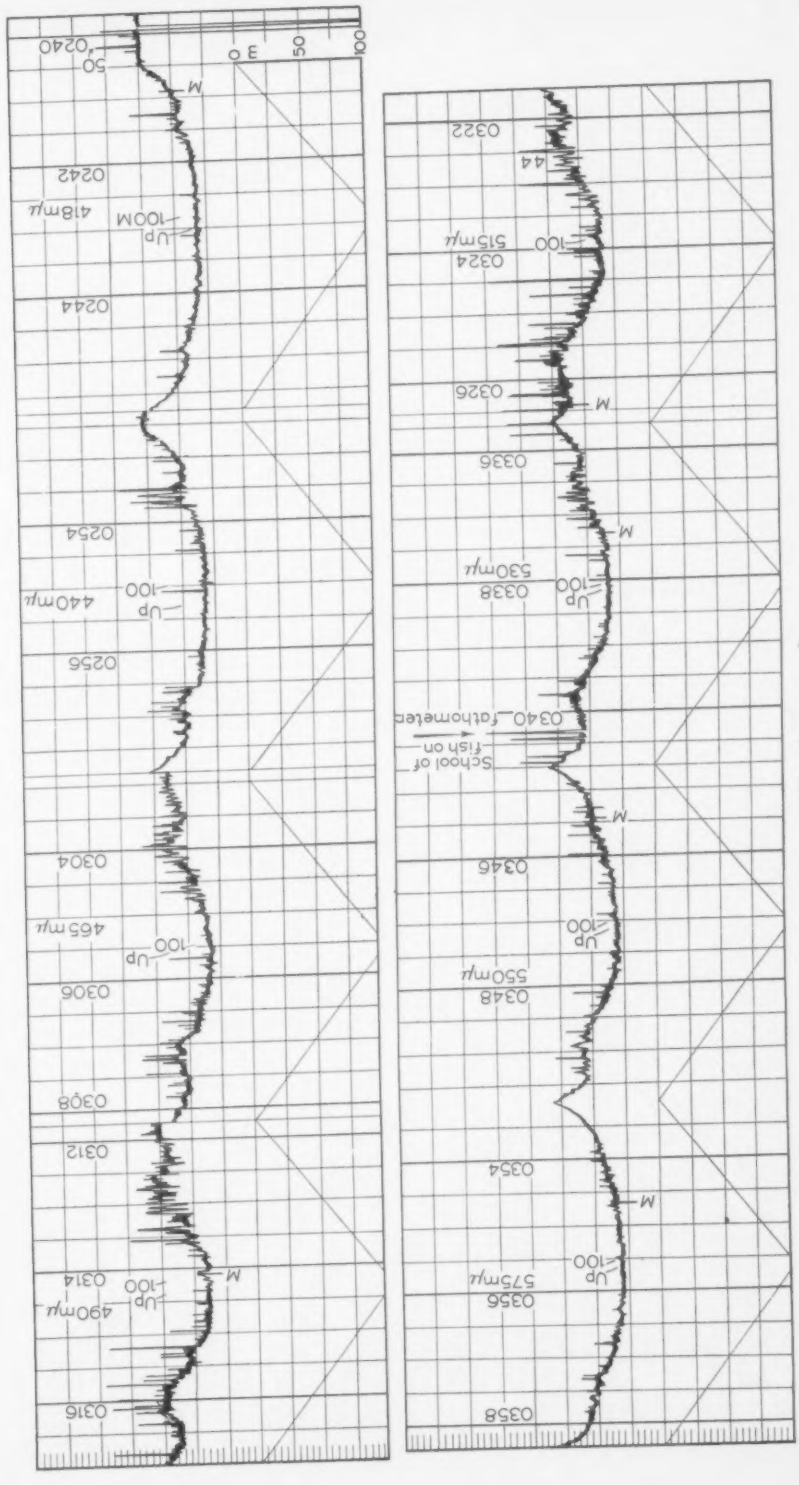

Fig. 4 *continued.*

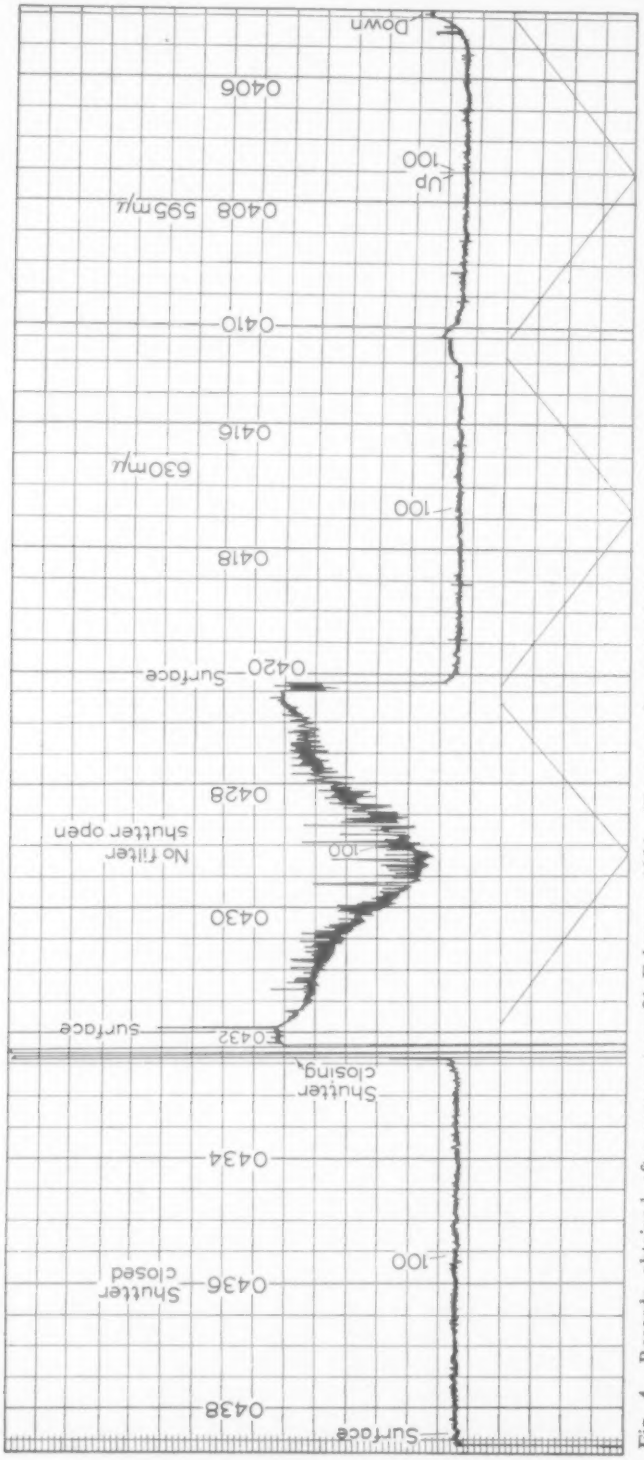

Fig. 4. Records obtained after moonset on 21 February, 1956. The trace for each of the ten interference filters, the meter with no filters and with the shutter closed, shows the photometer lowering to 100 metres (right half) and the return to the surface (left half).

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higher concentration, rather than of greater luminescent activity, of individuals. It is probable that neither alternative is achieved and that changes in concentration and activity combine to produce the observed effect.

Support for the opinion that luminescent activity of the individual actually increases during the periods of vertical migration is offered by the direct correlation between luminescent activity and oxygen consumption established for other organisms whose luminescence has been studied (HARVEY, 1952). If the light-producing members of the scattering-layer fauna are not anomalous in this respect, one would predict that an increase in respiratory rate of the magnitude probably encountered during the rapid vertical migrations should be accompanied by an increase in luminescent output.

A third possibility exists – that the increment in light production is occasioned by the presence of other luminescent organisms in the water column. The acoustic dimensions of these other forms might be inadequate to cause detectable sonic scattering, and they need not migrate if their vertical distribution were uniform above the level of the layer. Their luminescent activity could be influenced by some stimulus provided by the migrating sonic scatterers. The critical stimulus could not be simple mechanical agitation, for we have been unable to detect such general luminescence in the water column above the sonic-scattering layer, even when the photometer was moved, sensor looking downward, at a rate of 35 metres per minute. Strength for such an argument may be derived from the work of BURGHAUSE (1914) with *Pyrosoma*. The luminescence of this colonial tunicate is suppressed by exposure to continuous sunlight, but stimulated by intermittent light. *Pyrosoma*, or any other form with a similar behaviour pattern, could be stimulated to luminesce by the approach of luminescent sonic scatterers, and the high frequencies of the flashes observed during the migratory periods may represent the sum of the luminescent activities of migrating and non-migrating organisms.

Experiment 3. At 0240 hours, one hour after moonset on 21 February, the ship's lights were reduced to a minimum, and a series of twelve photometer lowerings was begun. The sensor was oriented to look upward. In these casts ten interference filters were used, covering a spectral range from 418 to 630 mμ. One lowering without filters, and one with the shutter closed were made as well. The instrument was sent to 100 metres each time and then returned immediately to the surface (Fig. 4).

Throughout this period a scattering layer was detectable at a stable depth of about 30 metres. Flashes of light were detected from 25 metres downward. The spike heights (millivolts) recorded with each filter in the 25 to 60-metre layer of the water column were tabulated, and the intensity of irradiance corresponding to each spike height was calculated from equation (2).

SPECTRAL DISTRIBUTION OF LIGHT GENERATED IN A SONIC-SCATTERING LAYER

Examination of the individual records in Fig. 4 reveals that on every photometer lowering, except those casts with filters at the extreme red end of spectral range, an increase in the intensity of light was encountered as the instrument passed downward from 25 to about 40 metres. Similarly, as the photometer moved toward the surface (left half of each record) the intensity decreased in this water layer.

In the blue to green region of the spectrum, the intensity of one or more of the flashes recorded at depth was greater than the intensity of the light of the same wave length at the surface. In the 460 to 490 mμ range the intensity of the brighest flash was four to five times as great as the intensity at the surface.

The curve representing the spectral distribution of the brightest of the flashes recorded at each wave length (solid line, Fig. 5) is highest near 485 mμ and decreases quite regularly toward the blue and red. The spectrum derived from the mean values of irradiance of the flashes at each wave length (broken line, Fig. 5) peaks near 478 mμ and is similar in shape to the spectrum of the brighest flashes except at the extreme blue end where the mean spectrum shows no secondary rise. Each point on the mean curve is based on 30 to 48 individual flashes, and it is probably more representative of the distribution of colour in the light generated at depth than is the maximum intensity spectrum.

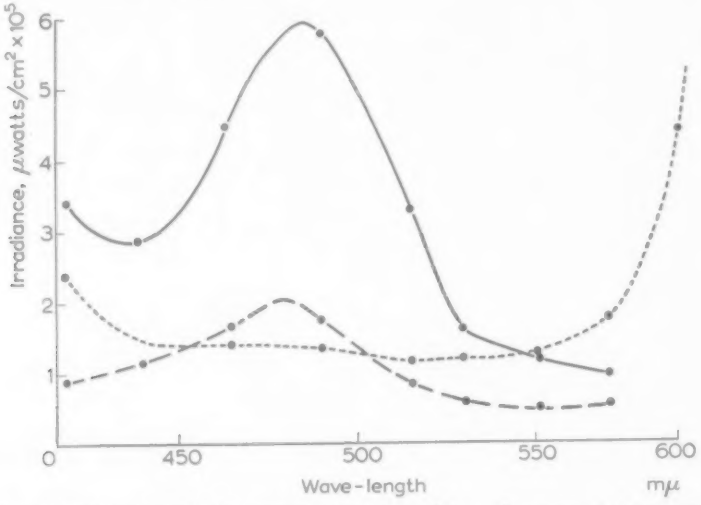

Fig. 5. Spectral distribution of light generated *in situ* at 25 to 60 metres (brighest flashes, solid line; mean intensity, broken line) and of light from sky and ship detected at the surface (dotted line) between 0240 and 0350 hours on 21 February, 1956. The three curves have been constructed from irradiance values obtained when equation (2) was applied to the data in Fig. 4.

The curve showing the spectral distribution of light from the ship and sky recorded at the surface (dotted line, Fig. 5) is low and quite flat in the 440 to 550 mμ range, but rises sharply in the red. A comparison of this curve with the other two obviates argument that the flashes recorded in the 25 to 60-metre water layer could have been artifacts produced by wave action or tilt of the photometer.

The time interval encompassed by the experiments on which the spectra are based was 77 minutes, and it is possible that during this period changes occurred in the character of the luminescent fauna of the scattering layer as well as in the excitability of individual organisms. No suggestion of such a change, however, could be found on the fathogram; the depth of the scattering layer and the intensity of the trace did not vary perceptibly. Dense, patchy scattering near the surface was recorded at 0340 to 0342 hours, and light flashes which may have been associated with these shallow sonic-scatterers were detected at a depth of 10 to 15 metres on the 515 mμ filter cast.

Downward movement of the scattering layer did not begin until 0540 hours, more than 100 minutes after the last observation used here to determine the colour of the light generated at depth.

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The constancy of the fathogram record and the fact that the interval of the measurements was well separated from the onset of the twilight period during which the degree of luminescence increases, lend support to the assumption that the spectra in Fig. 5 – and particularly the mean spectrum – are valid estimates of the colour of the light which was generated by organisms associated with the sonic-scattering layer.

Experiment 4. Collection with a one-metre closing plankton net through the sonic-scattering layer yielded three forms: chaetognaths, euphausiids, and myctophids, whose swimming rates might have allowed them to take part in the rapid twilight migration. Of these, only the euphausiids and myctophids luminesced. *Pyrosoma* was also abundant in the surface waters, and, while it undoubtedly contributed to the light production, it could not have been a part of the migratory layer.

The myctophids died shortly after capture, but specimens of *Euphausia pacifica* and *Pyrosoma atlantica* survived transport to the laboratory where the luminescence of individuals could be measured.

Several methods (mechanical agitation, electric shock, chemical irritants) were tried to stimulate euphausiids to luminesce in the laboratory. Of the techniques tested so far, the most reliably reproducible results are obtained when dark-adapted specimens are treated with ammonia and the maximum intensity of the terminal or death glow is measured.

Adult specimens of *E. pacifica* were kept in darkness from 2100 hours, when they were captured at sea, until 0230 hours the following morning, when mesurements were begun. These animals were exposed subsequently onlv to the light from a Wratten No. 2 (red) safelight.

Three specimens were removed from the dark chamber to a one-centimetre absorption cell containing 3 millilitres of sea water. The cell was placed in front of the integrating plastic window of the photometer which had been used previously for measurements at sea. The red safelight was turned off, the shutter of the photometer was opened, and 0·3 millilitres of 40% NH_4OH was pipetted into the absorption cell. The animals emitted a bright glow which appeared blue-green to the human eye. The glow faded gradually over a period of $1\frac{1}{2}$ to 2 minutes. A series of experiments showed that with specimens of uniform size the greatest difference between any two groups of three individuals was 0·15 millivolts in maximum recorder reading. In 50% of the tests the difference was less than 0·04 millivolts.

The process described above was repeated ten times with each of ten interference filters in the light path of the photometer (Fig. 6). Irradiance at each wave length was calculated from equation (2), using the maximum recorder reading after stimulation for the value of n.

Specimens of *Pyrosoma atlantica* were handled in a manner similar to that used for *E. pacifica*. A colony was placed in a beaker of sea water in front of the integrating plastic window of the photometer. After the safelight had been turned off and the photometer shutter opened, 40% NH_4OH was added in the ratio of 1 volume NH_4OH to 10 volumes of the sea water already in the beaker.

Preliminary experiments showed that following stimulation with ammonia the terminal glow was maintained for several minutes. The glow was long enough that a single specimen could be used for measurement at several wave lengths. The interference filter with maximum transmission at 490 mμ was used as a reference filter, and a measurement at this wave length was made before and after each other measurement (Fig. 7). By drawing a continuous line through each set of reference filter records it was possible to estimate the 490 mμ emission level at the time of each other measurement. Irradiance at each test level and at the corresponding 490 mμ reference level was calculated from equation (2).

The value $H\lambda_0$ for irradiance immediately after stimulation was computed for each wave length by

$$H\lambda_0 = \frac{H\lambda H_{r0}}{H_r} \qquad (3),$$

where $H\lambda$ is the observed irradiance at the test wave length at the time of measurement, H_r is the simultaneous irradiance level at the reference wave length, and H_{r0} is the maximum irradiance measured through the reference filter immediately after the animal had been treated with ammonia.

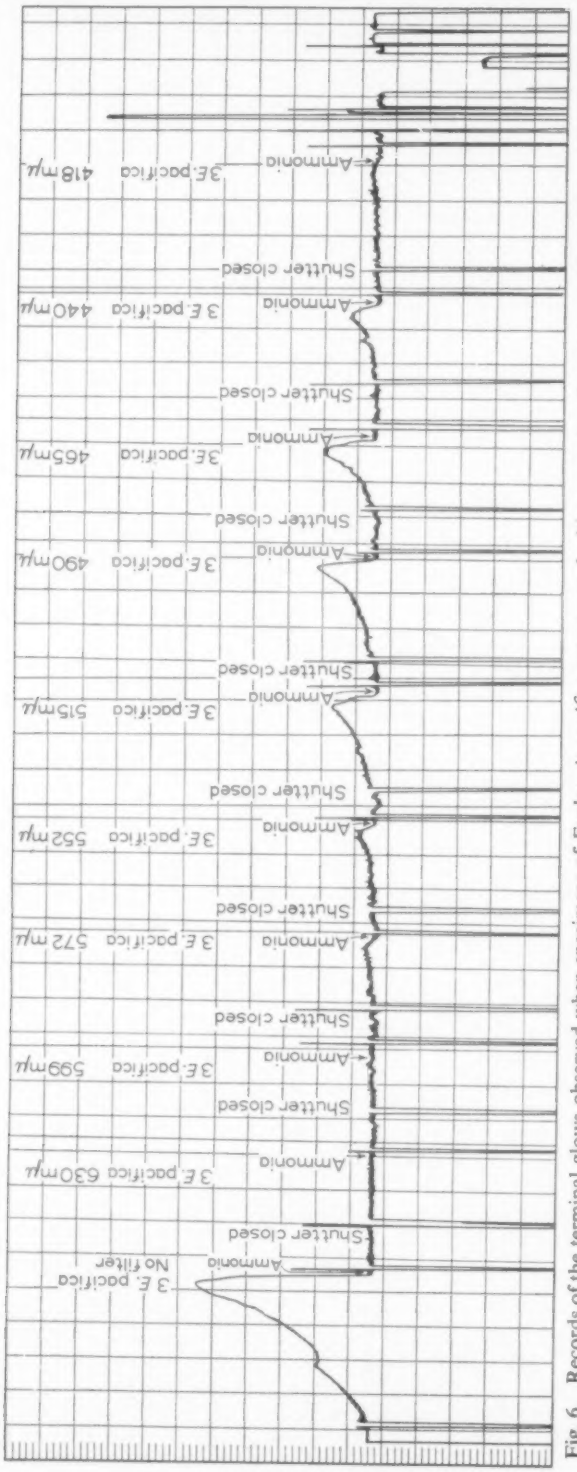

Fig. 6. Records of the terminal glows observed when specimens of *Euphausia pacifica* were treated with ammonia. One of ten series of tests with interference filters in the light path of the photometer and one test without filters are shown.

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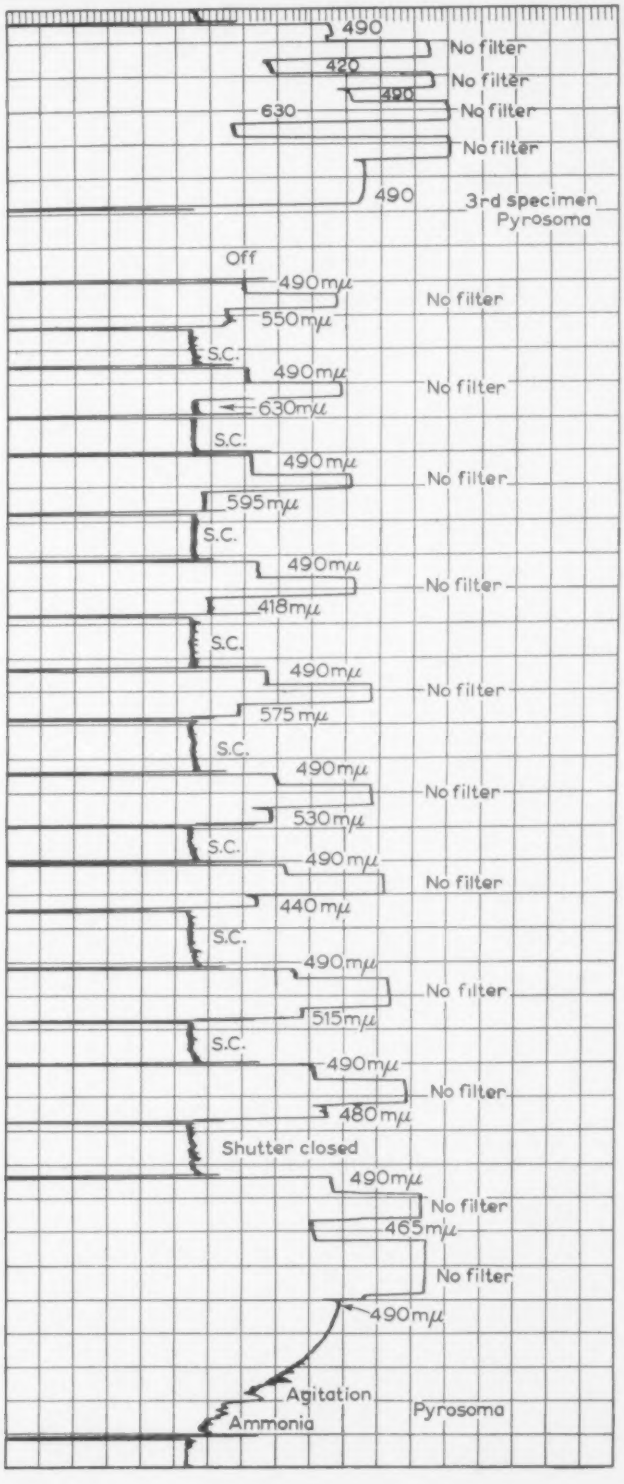

Fig. 7. Record of the terminal glow of a single *Pyrosoma atlantica* colony (one of 14 colonies measured) detected by the photometer when various interference filters were placed in the light path. Measurements through the reference filter (490 mμ) alternate with test measurements.

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LUMINESCENCE OF *EUPHAUSIA PACIFICA* AND *PYROSOMA ATLANTICA*

The maximum intensity of total irradiance recorded during the terminal glow from individual adult specimens of *Euphausia pacifica*, killed with ammonia within eight hours of capture, was found to vary within narrow limits from 1·6 to 2·0 $\times$ 10^{-3} microwatts per square centimetre at a distance of one centimetre. It should be mentioned that the luminescent terminal glow is possibly composed of many flashes of such short duration and high frequency that the photometer, like the human eye, is incapable of resolving them. The recorded intensities of the terminal glows presented here, therefore, may be erroneously low. The mean of the values obtained in the experiments is 1·8 $\times$ 10^{-3} microwatts per square centimetre at a distance of one centimetre, and the relative spectral distribution of this discharge is represented by the curve (broken line) in Fig. 8. The spectrum is consistently bimodal with a

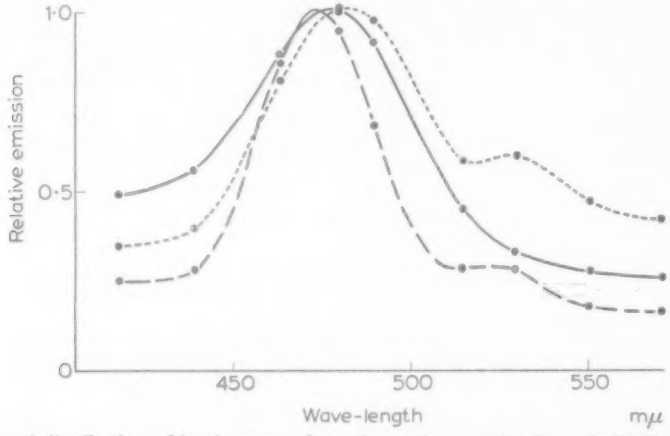

Fig. 8. Spectral distribution of luminescence from the sonic-scattering layer (solid line), *Euphausia pacifica* (broken line) and *Pyrosoma atlantica* (dotted line). Data on which the curves were based have been equated to 1·0 at the point of maximum emission.

primary peak at about 476 mμ and a lower, secondary peak between 515 and 530 mμ. The ratio between the heights of primary and secondary peaks is about 1 : 0·3.

E. pacifica, like most other euphausiids, possesses ten photophores, one on each eyestalk, one at the base of each of the paired second and seventh thoracic appendages, and a median one on each of the first four pleopods. When the animal is excited strongly by physical or chemical means, all of the photophores emit light, apparently simultaneously. Each light organ is quite distinct to the dark-adapted observer, and the glow may persist for as long as twenty seconds while the animal darts about its container looking like a miniature passenger train racing through the night.

Euphausiid luminescence is thought to be intracellular and under nervous control (HARVEY, 1952). The ability to luminesce is not lost with death, and the light organs of specimens which have been deep-frozen for several weeks will flash brightly when the dead animals are handled. If one cuts into a photophore, while dissecting out an eye for instance, the luminescent material is released, runs out in a bright stream and disperses in the water in the dissecting dish. In one instance, after 300 eyeless, discarded corpses had been collected on a bit of cheesecloth, the cloth was wrung

out at the end of the dissections. The light emitted by the expressed fluid was bright enough that the outline of a microscope could be seen by it, and scissors and forceps on the bench could be distinguished readily in a room that was otherwise entirely dark.

The intensity of total irradiance recorded from *Pyrosoma atlantica*, killed with ammonia within eight hours of capture, varied with the size of the specimen. A colony 10 centimetres long emitted light having an initial maximum total irradiance of $2{\cdot}5 \times 10^{-2}$ microwatts per square centimetre at a distance of one centimetre. The relative spectral distribution of the light (dotted line, Fig. 8) was extremely constant from specimen to specimen. The emission spectrum, like that of *E. pacifica*, is bimodal with a primary peak at about 482 mμ and a secondary peak near 525 mμ. The ratio of the heights of primary to secondary is 1 : 0·6.

Luminescence in the genus *Pyrosoma* is thought to be caused by symbiotic bacteria located in the two or more light organs at the distal end of each member of the colony (HARVEY, 1952). The luminescence has been described from visual impressions, and much disagreement exists as to its colour. PÉRON (1804) reported that he saw it change from red through yellow and green to sky-blue. Such a change was not detected here during the 20- to 30-minute intervals through which the terminal glows persisted. The order in which filters were used was reversed on alternate specimens, and no differences could be found in the resulting relative spectral distributions of the emission.

The relative spectral distribution of light generated in the sonic-scattering layer on the night of 20-21 February (solid line, Fig. 8) peaks midway between the maximum for *E. pacifica* luminescence and that for *P. atlantica*, and neither organism can be disqualified as a contributor to the light produced at depth. It seems a certainty that *Euphausia pacifica*, a form commonly included in the sonic-scattering layer fauna in the San Diego Trough, was responsible, at least in part, for the flashes observed. The colour of the light emitted is consistent with this opinion, and the intensity of *E. pacifica*'s luminescence is within the intensity range of the light generated at depth.

Similarly, it seems likely that *Pyrosoma atlantica*, while it cannot have been part of the sonic-scattering layer during the rapid twilight migration, contributed to the light detected in the water column. Although the *P. atlantica* colonies appeared to be restricted to the water immediately below the surface on that night, the intensities of total irradiance (8×10^{-3} to 4×10^{-2} microwatts per square centimetre at a distance of one centimetre) recorded from individuals in the laboratory were from ten to fifty times the intensity (8×10^{-4} microwatts per square centimetre) of the light from the sky and ship recorded at the sea surface during the night of 20-21 February.

Emission spectra of *Gonyaulax*, obtained with a monochromator by Dr. Beatrice Sweeney of this Institution, are maximal near 470 mμ. Similar spectra obtained with our photometer peak near 480 mμ. This discrepancy may be occasioned by the difference between the widths of the spectral bands produced by the monochromator and those transmitted by the interference filters. It is possible that a difference might be observed between the emission spectra presented here for *E. pacifica* and *P. atlantica* and those which could be obtained by other methods. While such a difference would be important in determining the precise emission spectrum

of any particular animal it cannot affect a comparison of the results presented here, for all observations were made with the same instrument.

GENERAL CONSIDERATIONS

The *in situ* generation of light in the sea at intensity levels high enough to be detected readily by modern photometric techniques presents a problem to the oceanographer who seeks to study the transmission of sunlight or moonlight in the oceans. Each discrepancy in an otherwise regular set of observations must be examined with redoubled caution before it can be evaluated as a physical characteristic of the water mass, an instrumental idiosyncracy, or a biological phenomenon. Often the appropriate classification will be impossible to determine.

One of us (KAMPA, 1955a) has described the extinction of sunlight with depth in the water off San Diego. Two inflections are commonly found in the extinction curve, one at about 100 metres – presumably associated with the lower margin of the euphotic zone, and a second regularly encountered at the level of the sonic-scattering layer. The curve in Fig. 1 of the present paper is typical of the pattern, if the spikes from about 250 metres downward are ignored. The two layers of higher extinction have been explained on the basis of concentrations of light-absorbing and light-scattering particles in the water.

Nothing in the bioluminescent data suggests that the upper inflection requires another interpretation, for the intensities of transmitted sunlight encountered between the surface and 100 metres are from one hundred to one million times as great as the brighest of the luminescent flashes ever recorded in the area.

Bioluminescence could affect the interpretation of the inflection at the level of the sonic-scattering layer, however. If on the cast represented by Fig. 1, the photometer had begun to detect luminescence from the layer at about 225 metres, and if this luminescence had been maximal near 290 metres, the apparently higher extinction from 290 to 350 metres could be caused simply by the instrument's retreat from the zone of greatest luminescent activity. The instrument used to collect the data on which KAMPA's (1955) conclusions were based employed a meter with a much slower response than that of the electric recorder, and flashes could conceivably have gone undetected.

The biologist is placed in an even greater quandary by the introduction of records of bioluminescence. It has been shown (KAMPA and BODEN, 1954) that when a photometer is held some 10 metres above the sonic-scattering layer in the San Diego Trough, the depth of the layer throughout the twilight migration can be correlated with the depth of an isolume. Observations over a two-year period have shown that the mean intensity of this isolume is 1×10^{-4} microwatts per square centimetre, and we have reasoned that at least some of the organisms in the layer move upward and downward in an attempt to keep their environmental light level constant. Such reasoning is clouded by the discovery that the layer itself is producing light of the same mean intensity as that with which the layer migrates and that individual flashes are commonly ten to one hundred times as intense.

A sonic-scatterer whose depth distribution is photoregulated, but which does not luminesce itself, would be exposed to conditions similar to those met by the photometer. If, as we believe, *Euphausia pacifica* is one of the photoregulated scatterers, the situation is even more complex, for the irrradiance level of the luminescence from

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an individual organism may be as high as 2×10^{-3} microwatts per square centimetre at a distance of one centimetre. This intensity seemingly represents the sum of the activities of ten photophores, and the light produced by the photophore in the eye stalk would then have an intensity of 2×10^{-4} microwatts per square centimetre at a distance of one centimetre. The distance from the centre of this photophore to the centre of the eye is about one millimetre in specimens of the size used here, and by the inverse square law, the intensity of a single flash must be of the order of 2×10^{-2} microwatts per square centimetre at eye-level.

Furthermore, the emission spectrum of this luminescence is maximal near 476 mμ, and the absorption of the photosensitive material extracted from *Euphausia pacifica* eyes (KAMPA, 1955b) is maximal near 465 mμ. If one assumes only 50 per cent efficiency in the system, the animal is still presenting its photosensor with intermittent stimuli of one hundred times the intensity of the constant environmental stimulus to which it is responding.

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We should like to thank Professor ALISTER C. HARDY, F.R.S., Oxford University, England; Professors ROGER REVELLE, CARL ECKART, MARTIN W. JOHNSON, and CARL L. HUBBS, DR. FRANCIS T. HAXO, Dr. WHEELER J. NORTH, and Mr. JOHN E. TYLER of the Scripps Institution, for their continued interest in the work and for their stimulating criticism of the manuscript.

University of California
Scripps Institution of Oceanography
La Jolla, California

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Some further deep current measurements using neutrally-buoyant floats

J. C. SWALLOW

(*Received* 8 *January* 1957)

Abstract—Nine more observations have been made since a previous account was written (SWALLOW, 1955) of the design of a neutrally-buoyant float and its use in current-measuring. Currents ranging from 22 to 0·8 cm/sec have been measured, at depths between 340 and 2,900 metres. Some improvements have been made in the method of tracking the floats, and in determining the depths at which they become neutrally buoyant.

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LISTENING ARRANGEMENTS

FOR the first experiments, in June, 1955, the hydrophones were nickel scrolls similar to those used as transmitters on the floats. They were suspended on twin cable to a depth of about 7 m and weighted with sounding leads to keep the cable approximately vertical. Being omnidirectional, these hydrophones suffered badly from noises generated inside the ship and from waves striking the ship's side. They were made quieter by attaching them to lines passed under the ship, backing the scrolls with sponge rubber to prevent direct contact with the hull. This arrangement had the advantage that the separation of the hydrophones, and the bearing of the line joining them relative to the ship's head, were fixed more accurately. However, work was possible only in winds less than force 5 and with waves less than about 2 metres high.

For the April-May 1956 cruise, directional barium titanate hydrophones were borrowed from the Admiralty. They were tuned to 10 kc/s and had a beam angle of about 90°. Two of them were lowered over the ship's side to a depth of about 5 m, facing vertically downwards. Interference from noises in the ship and at the sea surface was much reduced, and it was possible to work with floats at a few hundred metres depth in force 7 winds and with waves about 5 m high. The limit was imposed as much by the difficulty of seeing the anchored marker buoys on the radar, as by the increased background noise on the hydrophones.

DEPTH MEASUREMENT

The depths reached by the floats in most cases have been estimated by a method previously described. The length l (Fig. 1a) was obtained by plotting successive bearings from radar fixes of the ship's position, and the angle α determined from the maximum difference in times of arrival of signals from the float at the two hydrophones. This method was unsatisfactory since any error in fixing the float in a horizontal plane was included in determining the depth. The accuracy usually obtained was $\pm$ 200 to 300 m in depth, whatever the depth of the float.

A better method has been used with some of the shallower floats on the April-May 1956 cruise. A pair of omnidirectional hydrophones about 40 m apart was lowered

vertically to various depths (Fig. 1b) and the difference in times of arrival of signals from the float at the two hydrophones was observed. The angle between the vertical and the ray from the float to the mid-point of the hydrophones could be obtained from this time difference, and plotting these rays at each depth gave the depth of the float and its horizontal range. No conductor-cored wire rope was available, and the electric cable to the hydrophones was lashed to 4 mm wire with a 25 kg weight on

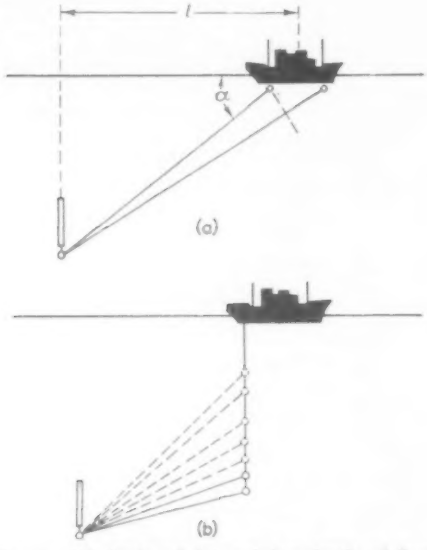

Fig. 1. Methods of determining depth of float.

the end. The wire angle could be kept within about 5° of the vertical by using the ship's engine, which did not cause much interference. Any drift of the ship during the lowering could be observed by radar and a correction made, though it was usually negligible. The accuracy of a single observation of depth by this method was about ± 30 m.

It might be more convenient to track a float entirely by observations of this kind, without taking horizontal bearings. The ship could be kept hove-to, instead of having to fall off in order to change the ship's heading, and with floats at great depths the advantage of putting the hydrophones much nearer the float might outweigh the losses in the electric cable.

Accurate depth measurements were made on four floats, and comparison of the observed and calculated depths showed that in each case the float had behaved as if an extra load of 6 (± 1) g had been added. This is explained partly by movement of the rubber sealing rings, which slide to the outer edge of their grooves when the plugs are fitted into the tubes, and are pushed inwards, and compressed, when the water pressure is applied. Previously an allowance of 4 g had been made, for this effect, in calculating the load required for a given depth; 6 g will be allowed in future.

The consistent behaviour of these floats, within ± 1 g load which is roughly equivalent to ± 30 m depth, suggests that the depth measurements were reliable and that no significant vertical oscillations of the floats occurred.

COMPRESSIBILITY AND COLLAPSING DEPTH OF TUBES

A direct measurement of compressibility was made on a length of $1\frac{7}{8}$" O.D. $\times$ 9 S.W.G. aluminium alloy tube. The value obtained was 15 ($\pm$ 1) $\times$ 10^{-12} cm^2 dyne^{-1}. That calculated from the observed velocities of elastic waves in a sample of the alloy was 17 $\times$ 10^{-12} cm^2 dyne^{-1}. The uncertainty in compressibility corresponds to an uncertainty in calculated depth of approximately 3%.

Several pieces of tube were collapsed in a pressure tank, and the maximum depth for the 9 S.W.G. tubes used in the floats was found to be 4,600 m. This is little more than half the depth calculated from the tabulated value of the strength of the alloy. The maximum depth curve given previously (SWALLOW, 1955) is much too optimistic. Several lengths of the 9 S.W.G. tube have been tested to 4,000 m, and it seems likely that, considering mechanical strength alone, the floats could be used down to that depth in their present form. For greater depths, thicker-walled tube or a higher-strength alloy would be needed.

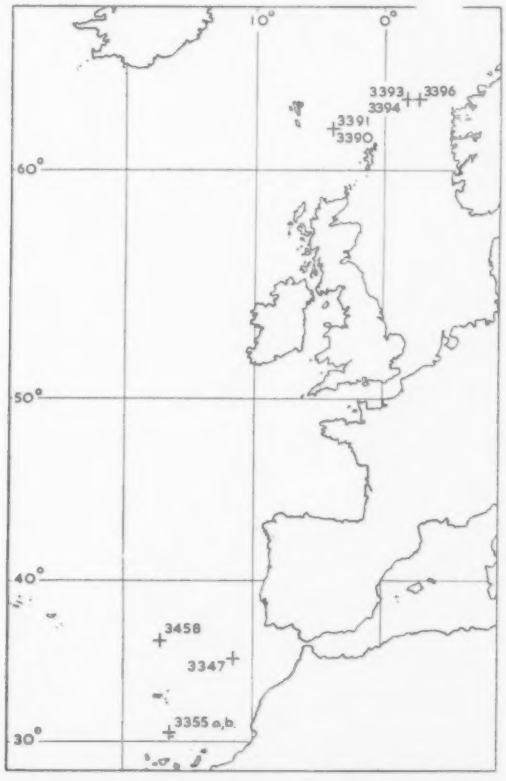

Fig. 2. Positions of current-measuring stations.

OBSERVATIONS

These measurements were made on three cruises of the R.R.S. *Discovery II*, at the station positions shown in Fig. 2.

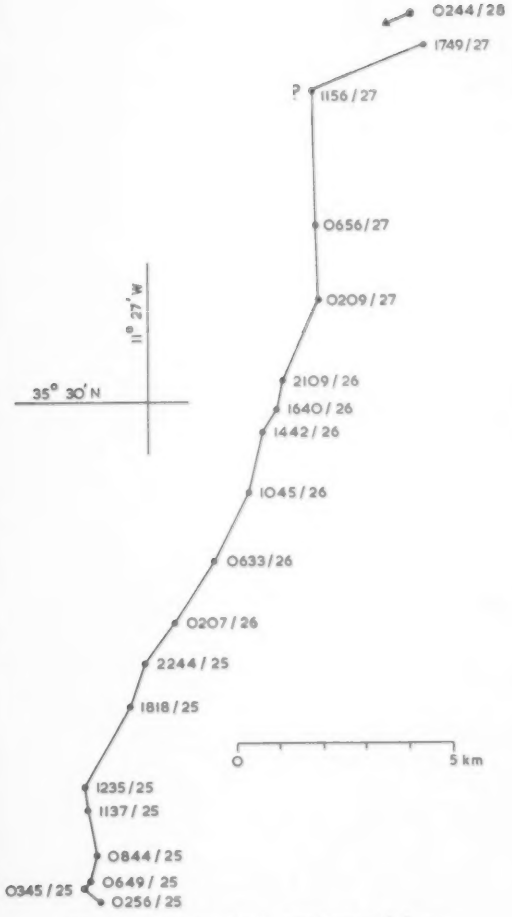

Fig. 3. Station 3347, positions of float.

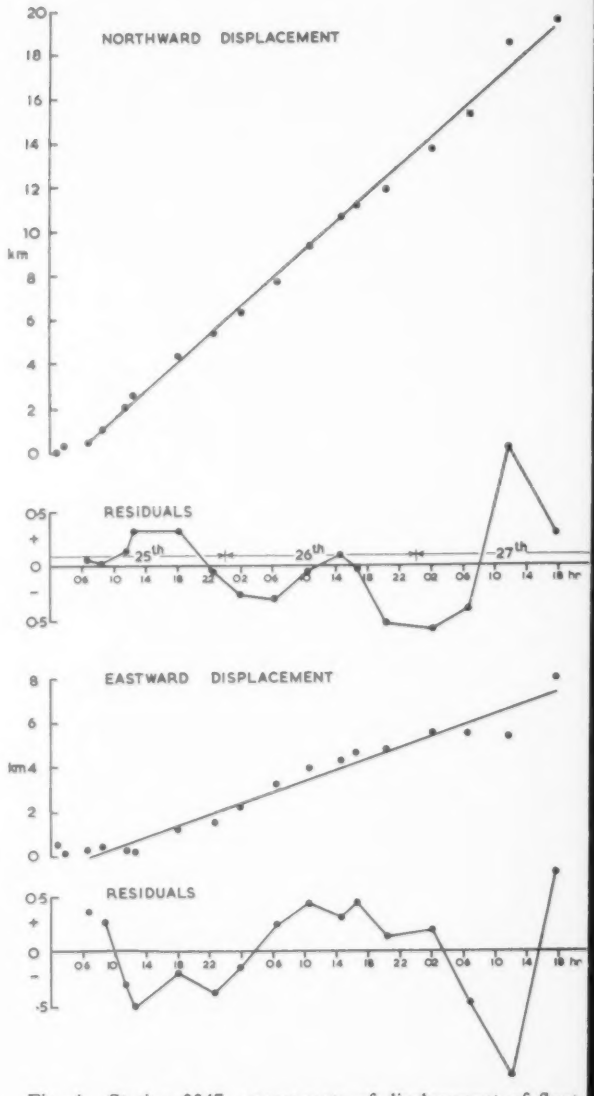
NORTHWARD DISPLACEMENT
km
RESIDUALS
25th
26th
27th
06 10 14 18 22 02 06 10 14 18 22 02 06 10 14 18 hr
EASTWARD DISPLACEMENT
km
RESIDUALS
06 10 14 18 22 06 10 14 18 22 02 06 10 14 18 hr

Fig. 4. Station 3347, components of displacement of float plotted against time.

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On the first of these cruises, two floats were lost as a result of electrical faults in the receiving equipment on board ship ; since then, each float used has worked satisfactorily. In each case the positions of the float were plotted by radar relative to an anchored buoy. The mean currents have been obtained by plotting the north-south and east-west components of displacement separately against time, fitting straight lines by least squares, and combining the slopes of these lines to give the resultant current and its direction. Positions obtained during the first three hours, when the float was sinking, have not been used in fitting mean currents. In some

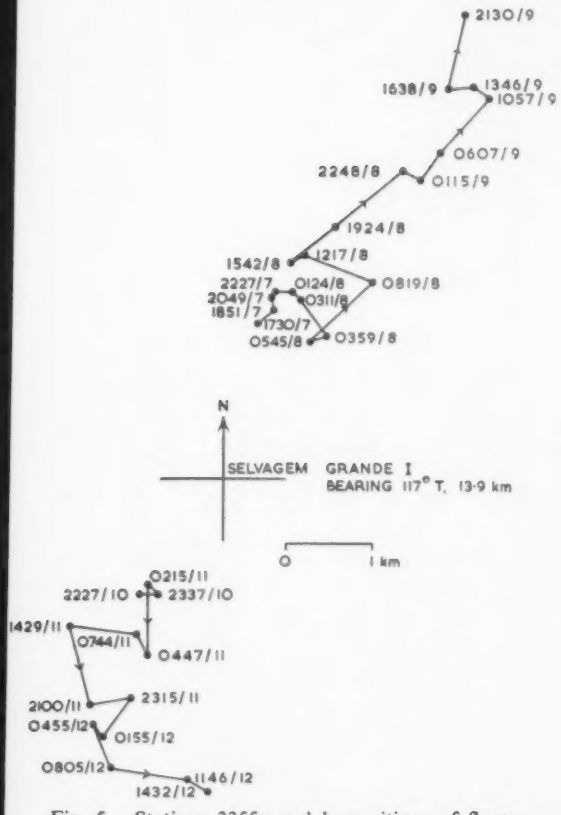


Fig. 5. Stations 3355a and b, positions of floats.

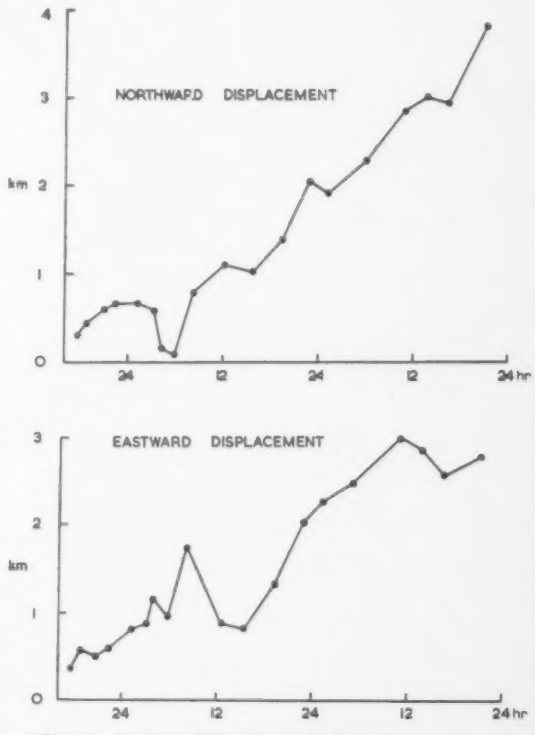


Fig. 6. Station 3355a, components of displacement of float plotted against time.

cases periodic fluctuations can be seen in the residuals, but the duration of the observations is too short, or the number of fixes too small, to allow determination of the periods and amplitudes of these oscillations. They have been ignored in fitting the mean currents, but the inaccuracy involved is small. The standard deviations have been calculated assuming that all the residuals are random, and may therefore be slightly too large.

Station 3347, 0256/25th – 0244/28th Oct. 1955 (G.M.T.), (Figs. 3 and 4). Depth 1200 ($\pm$ 200) m. Mean current 9·52 ($\pm$ 0·16) cm/sec, bearing 021°T ($\pm$ 1°). If

the last two fixes are omitted (because of worse scatter) the resultant becomes 9·24 (± 0·12) cm/sec, 022°T (± 1°). The position of the anchored buoy was checked by sounding over part of the boundary between a flat plain (depth 4865 m) and the north-eastward extension of Ampere bank. There is a possible 20-hr periodicity in the northward residuals, with amplitude approximately 0·25 km, corresponding to a current amplitude of 2·2 cm/sec. The period of inertial oscillations in this latitude is 20·6 hours.

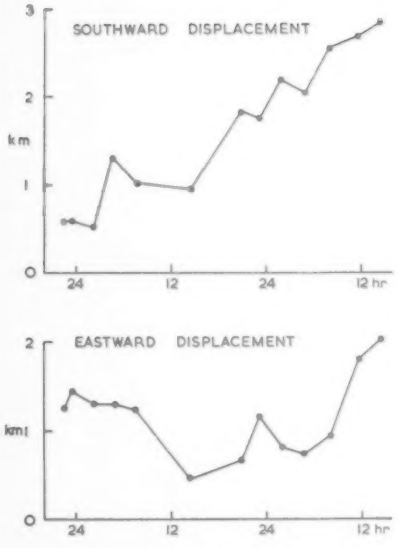


Fig. 7. Station 3355b, components of displacement of float plotted against time.

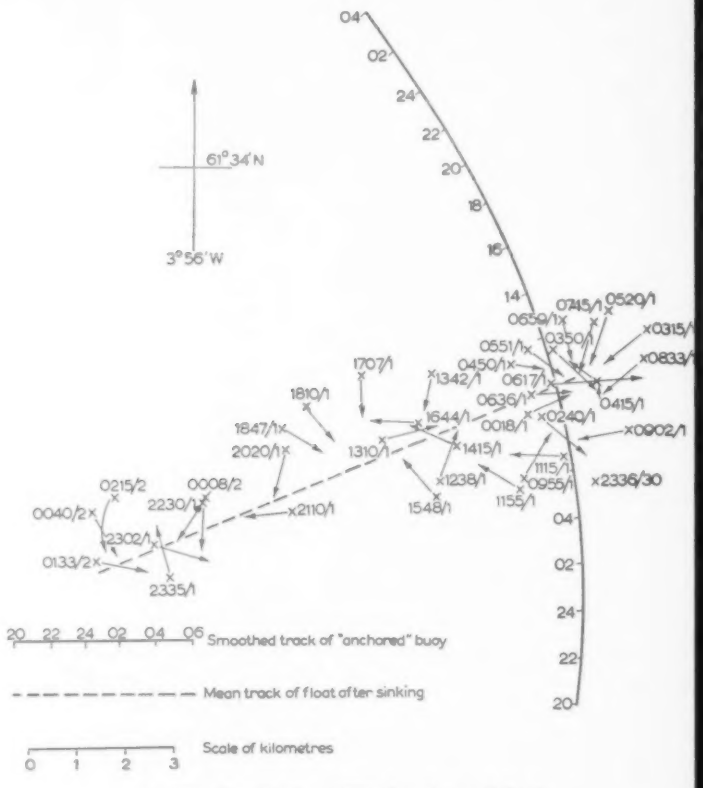


Fig. 8. Station 3390, bearings of float.

3355a, 1730/7th – 2130/9th Nov. 1955, (G.M.T.), (Figs. 5 and 6). Depth 1900 (± 200) m. Mean current 2·38 (± 0·15) cm/sec, 037°T (± 4°). Positions for this and the next float were checked by radar fixes on Selvagem Grande island. The buoy was anchored in 2644 m, with a fairly steep slope towards the island. There is some indication of a half-day tide in the northward residuals, corresponding to a maximum north-south tidal stream of about 3 cm/sec.

3355b, 2227/10th – 1432/12th Nov. 1955, (G.M.T.), (Figs. 5 and 7). Depth 1900 (± 300) m. Mean current 1·64 (± 0·19) cm/sec, 170°T (± 12°). During this observation the marker buoy broke adrift and was re-anchored twice; tracking was abandoned

when the buoy began to move seriously a third time. This result combined with the previous one suggested that the deep water may have been coming from the north-west, and was diverging in the area of the measurements to pass round the island.

3390, 2336/30th April – 0215/2nd May, 1956. (B.S.T.), (Fig. 8). Depth (estimated from added load) 840 (± 50) m. Mean current 13 (± 3) cm/sec, 250°T (± 20°). The

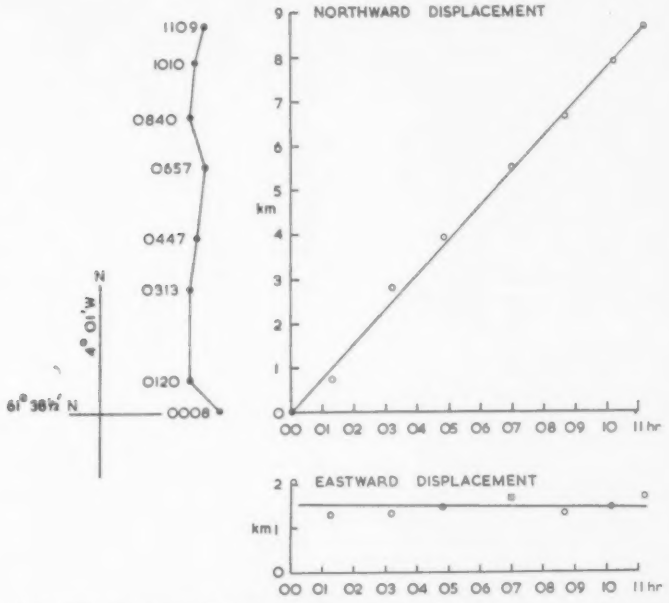


Fig. 9. Station 3391, positions of float and components of displacement plotted against time.

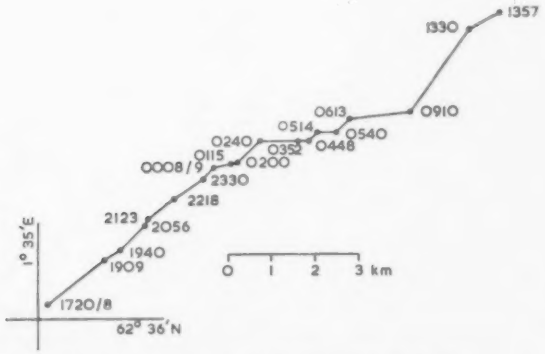
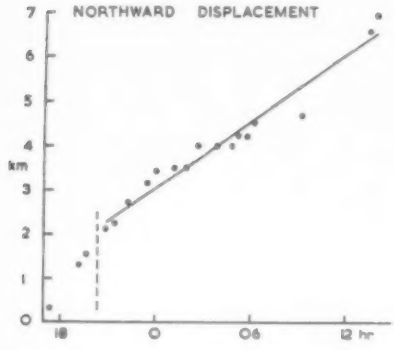


Fig. 10. Station 3393, positions of float.

only check on buoy positions in this part of the Faroe-Shetland channel was from Loran fixes, each having an uncertainty of about 2 km. They showed that the buoy dragged its sinker about 16 km N.N.W. during the observation, which was cut short by a sudden rapid drift when the buoy finally broke its mooring. The bearings obtained

on the float have been plotted relative to the track of the anchored buoy, assuming that the latter moved at a constant speed. No attempt was made to fit a mean track by least squares, and the standard deviations given are nothing more than plausible guesses.



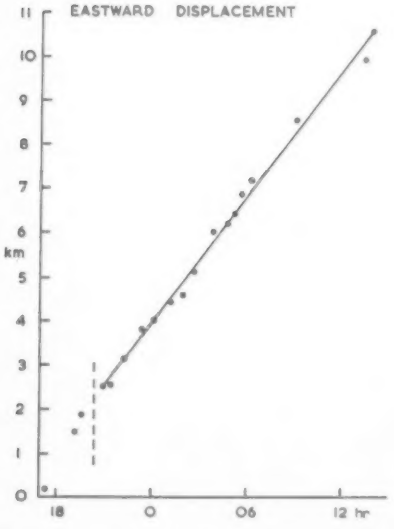


Fig. 11. Station 3393, components of displacement of float plotted against time.

Fig. 12. Station 3394, positions of float and drogue.
● Position of float.
○ Position of drogue.

3391, 2054/2nd – 1109/3rd May 1956. (B.S.T.), (Fig. 9). Depth 340 (± 20) m. Mean current 21·8 (± 0·5) cm/sec, 359°T (± 2°). This was in the same area as the previous measurement. The buoy was anchored more securely, and Loran fixes showed no significant movement. Two depth measurements were made using vertical hydrophones. The float was abandoned when out of radar range of the buoy, there being insufficient time for laying another and continuing the tracking.

3393, 1720/8th – 1357/9th May 1956. (B.S.T.). (Figs. 10 and 11). Depth 440 (± 30) m. Mean current 14·9 (± 0·3) cm/sec, 062°T (± 2°). This measurement and the two succeeding ones were made in the southern Norwegian sea, where it was difficult to check the anchored buoy positions by sounding or Loran. The buoys were anchored on 4 mm wire instead of the usual piano wire, with 5% to 15% scope, in depths between 800 and 600 m. Two separate 50 kg sinkers were used on

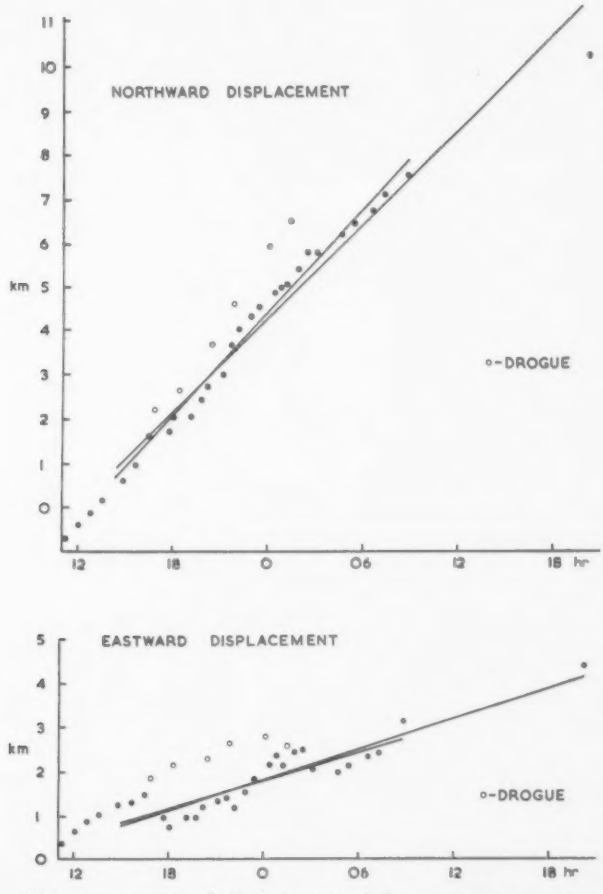


Fig. 13. Station 3394, components of displacement of float and drogue plotted against time.

each buoy. A movement of about 1 km in a NW–SE direction (at right angles to the depth contours) would have been detected ; it seems unlikely that any of the buoys moved during the observations. All three measurements were cut short by bad weather.

3394, 1119/10th – 2015/11th May 1956. (B.S.T.). (Figs. 12 and 13). Depth 480 (± 30) m. Mean current 10·3 (± 0·4) cm/sec, 018°T (± 2°). The long gap in fixes, from 0845 to 2015/11th, was caused by bad weather. The mean current over the period up to 0845/11th was 11·5 (± 0·3) cm/sec, 015°T (± 2°). A drogue

attached to a surface float by 450 m of piano wire was released at 1654/10th and tracked until 0125/11th. Its movement indicated a current of 14·9 (± 0·7) cm/sec, bearing 010°T (± 3°). During the same period the float at 480 m depth moved with a velocity of 13·4 (± 0·7) cm/sec, in the direction 018°T (± 4°). The wind at the time varied from 10 to 22 knots, backing from west to south.

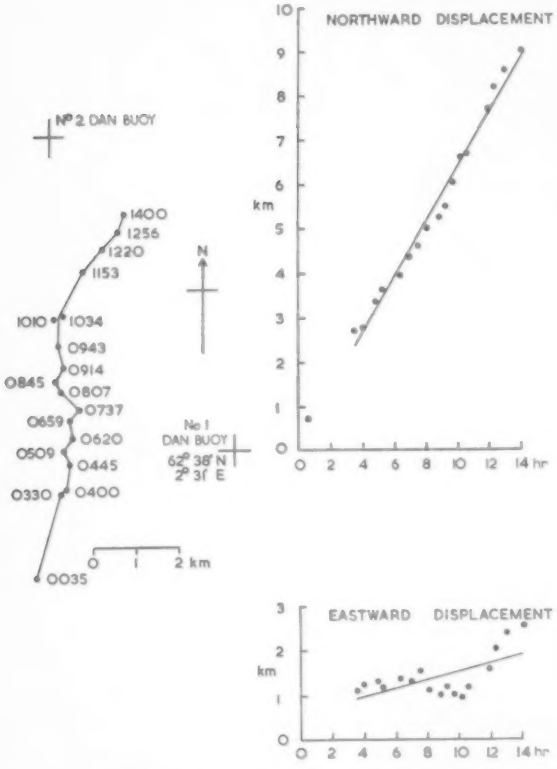


Fig. 14. Station 3396, position of float and components of displacement plotted against time.

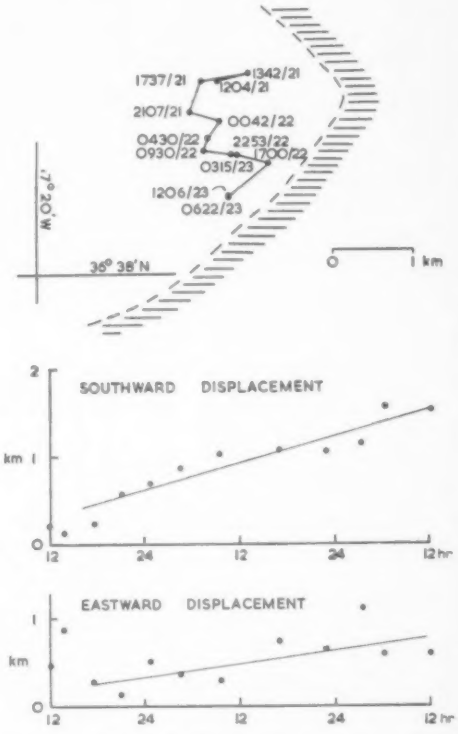


Fig. 15. Station 3458, positions of floats and components of displacement plotted against time.

3396, 0035 – 1400/13th May 1956. (B.S.T.). (Fig. 14). Depth 370 (± 30 approx.) m. Mean current 17·8 (± 0·6) cm/sec, 008°T (± 3°). The depth of this float was obtained by measuring the interval between the times of arrival of the driect sound from the float and that reflected from the sea bed, when the ship was sitting almost directly above the float. The track shows a marked curvature, which could be accounted for by a half-day tidal stream of about 6 cm/sec amplitude.

3458, 1204/21st – 1254/23rd Aug. 1956. (G.M.T. – 1). (Fig. 15). Depth 2900 (± 250) m. (Fig. 16). Mean current 0·8 (± 0·1) cm/sec, 153°T (± 8°). The position of the anchored buoy was checked by sounding across the sharply defined boundary between a rise and a plain. The depth to the plain was 5170 m. Fixes were too few for any periodicities to be clearly defined, but it seems unlikely that the half-day tidal range exceeded 0·7 km, corrosponding to a tidal stream of less than 5 cm/sec.

DISCUSSION OF RESULTS

A hydrographic section across the Faroe-Shetland channel was made on 28–30 April 1956, just before the direct measurements of currents in that area. Gradient-current calculations using two successive pairs of stations in the deep part of the channel showed currents at 300 m depth of 10·4 and 9·3 cm/sec across the section, relative to a depth of 800 m. The difference observed directly between depths of 340 m and 840 m was 29 ($\pm$ 4 approx.) cm/sec, in the same direction as the calculated current. The discrepancy is perhaps not surprising, in view of the variability of currents observed later in the Norwegian Sea.

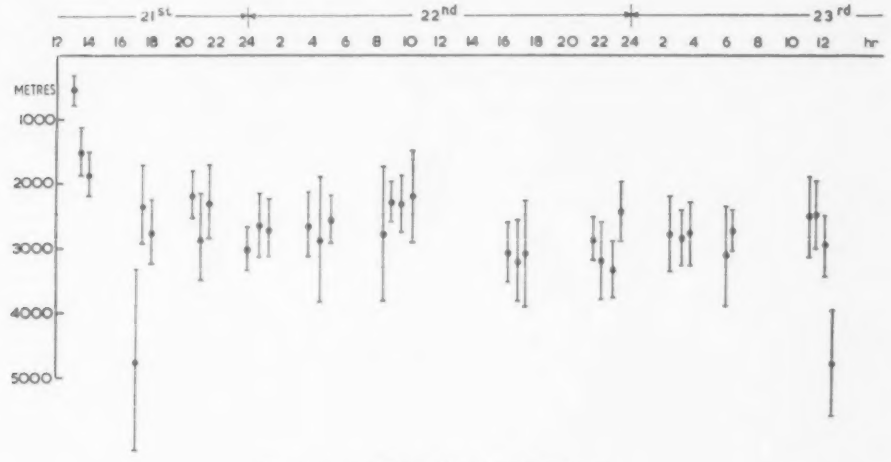


Fig. 16. Station 3458, depth estimates.

At the same time as the latter observations were made, the *Armauer Hansen* occupied several hydrographic stations in the area, and measured the current near the bottom at a position 14 km east of *Discovery II* stations 3393 and 3394. A mean current of 16 cm/sec in the direction 065°T was observed during 14 hours on 10–11 May 1956. The rapidly-changing conditions made it difficult to relate the current measurements in detail to the observed dynamic topography, though in general the currents were consistent with the known circulation in the Norwegian Sea (HELLAND-HANSEN and NANSEN, 1909; HELLAND-HANSEN, 1934).

The float used at station 3347, in the southern group of measurements, must have been in or very near to the Mediterranean water (WÜST, 1935), and the current might have been expected to have a more westward direction. Previous measurments by the *Armauer Hansen* (EKMAN, 1953, stations D and E) at a depth of 1000 m not far from this position, showed west-going currents of about 5 cm/sec.

The other three observations, at stations 3355 a and b, and 3458, were in the deep water, and are in fair agreement with DEFANT's (1941) picture of the currents at 2000 m depth deduced from hydrographic observations, if some allowance is made for the influence of topography.

The island near stations 3355 a and b has already been mentioned, and only 200 km from station 3458, in the direction of the observed current, is a group of seamounts

rising to within 1000 m of the surface and having a width at the 3000 m level of at least 220 km. For this reason, if for no other, the observed currents cannot be taken as " typical " of a large part of the eastern north Atlantic.

Although no half-day tidal streams have been fitted to these observations, it seems clear from the residuals that, at the four southern stations, they are unlikely to exceed 5 cm/sec, and are certainly much less than the average value of about 12 cm/sec given by Defant (1932) for these latitudes.

Possibly the contribution from internal waves of tidal period becomes less important at greater depths, so that the remaining tidal current may be near the theoretical value of about 3 cm/sec derived on the assumption that the tidal current is uniform over the whole depth.

Acknowledgements—The observations described above have involved the assistance of many colleagues on board the R.R.S. *Discovery* II. To them I should like to express my gratitude, in particular to Dr. A. S. LAUGHTON who took part in all the measurements, and also to Mr. E. C. FRENCH for his help in the earlier measurements and in building the floats. I am indebted to the Chief Scientist and members of the staff of H.M. Underwater Detection Establishment for their advise and assistance in providing transducers and hydrophones, and to the Post Office Research Station for pressure-testing facilities.

I should like to thank Dr. J. B. TAIT and Professor H. MOSBY for their co-operation in the experiments in the Faroe-Shetland channel and in the Norwegian Sea, and for permission to refer to unpublished results.

National Institute of Oceanography
Wormley,
near Godalming, Surrey

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Whales entangled in deep sea cables

BRUCE C. HEEZEN

(*Received 7 January* 1957)

Abstract—Fourteen instances of whales entangled in submarine cables are reported. Ten entanglements occurred off the Pacific coast of Central and South America. Six cases occurred in about 500 fathoms, with 620 fathoms the maximum depth reported. Five entanglements occurred in the period, February–March–April. All whales positively identified were sperm whales. The submarine cable was generally wrapped around the jaw and often around the flukes and fins. The cable was rarely broken but always badly mauled. The entanglements often occurred near former repairs where there is a chance for extra slack cable on the bottom. Two photographs of a sperm whale entangled in a cable and one photograph of a whale-jaw entangled in a cable are presented.

It is concluded that sperm whales often swim along the sea floor in depths as great as 620 fathoms. It is suggested that the whales become entangled while swimming along with their jaw plowing through the sediment in search of food. It is possible that the whales attack tangled masses of slack cable mistaking them for items of food.

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INTRODUCTION

THERE is considerable interest in the depths to which whales dive in the ocean. Physiologists are interested in the pressures that whales can withstand. Workers in underwater sound are interested in the depths where they can expect whale noises; the same workers when using fish-finding gear and interpreting fish and plankton scattering layers are interested in what depths they can expect echoes from whales. The depth to which whales dive to feed has significance concerning the food cycle in whale grounds.

It has been reported that a sperm whale dives to depths of 500 fathoms (LAURIE, 1933) as a sperm whale became entangled in a submarine cable being repaired in that depth. This conclusion was apparently based on a single report. The possibilities that the whale became entangled at an intermediate depth during repairs, or that the dead whale was carried there by a current from shallow water casts some doubt on this conclusion. The present paper present more information on the entanglement of whales in submarine cables at relatively great depths.

REPORTS OF DAMAGE TO SUBMARINE CABLES INFLICTED BY WHALES

Fourteen reports of cable damage by whales have been found on searching all available cable failure records of the Western Union Telegraph Company, the Commercial Cable Company, the All America Cable Company, and the Commercial Pacific Company (Table 1). Ten were off the Pacific coast of Central and South America (Fig. 1), one was in the Newfoundland area of the North Atlantic, two on the Atlantic coast of South America, and another off the west coast of India. The fourteen reports are given chronologically in the appendix.

There are nearly a half-million miles of cable laid on the sea floor in various parts of the world. In the appendix we have summarized the reported whale damage for about one-sixth of the world's cables. The list is considered complete for all whale

damage occurring in cables owned by the Commercial, All America, and Western Union companies for the years 1930-1955. The reports of cable damage kept by these companies are not nearly so complete or detailed for the years before 1930. In the records of the Commercial Cable Company all repairs are listed from the date of

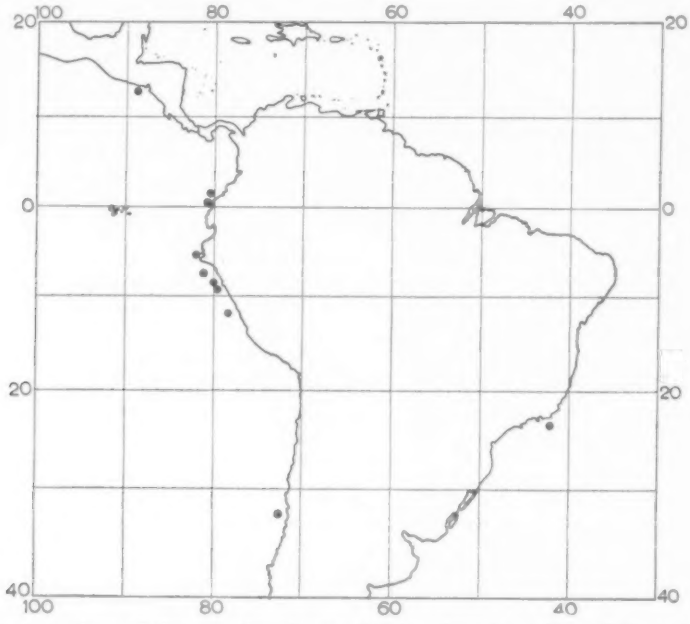

Fig. 1. Locations where whales were found entangled in submarine cables off Central and South America.

Table 1. *Cable failure records studied*

Teleghaph Company	*Years*	*Area*	*Number of cables*	*Number of whale breaks*
Commercial Cable	1882-1955	Transatlantic	8	0
" "		Eastern United States	10	0
Western Union	1872-1955	Transatlantic	10	0
" "		Eastern United States	18	1
" "		West Indies	9	0
" "		U.K. – Ireland	5	0
Commercial Pacific	1902-1951	Transpacific – China	1	0
All American Cable	1931-1955	Eastern United States	5	0
" " "		Caribbean	21	0
" " "		West Coast Central and South America	24	9

laying to the present. The All America and Western Union records in some instances are not quite so complete. Usually only a few words are devoted to the cause in the existing reports. Most of the detailed reports made before 1930 are no longer available.

A cable company memorandum dated 1905 refers to " whale damage in the Persian

Gulf (1872), Gulf of Suez (1892), and Prince William Sound (1905)," but gives no other details.

Dr. RAYMOND GILMORE (1955) recalls " one record of a humpback whale in a cable in Alaskan waters in comparatively shallow depths." Many more such reports will undoubtedly turn up as more cables are studied.

Fig. 2. (a). Drawing made from verbal description given by Captain J. HACK of the whale entangled off Peru in July 1940, in 470 fathoms. (See Appendix, No. 12).

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Fig. 2. (b). Drawing made from verbal description given by Captain P. E. HARNE of the whale found entangled March, 1931, off Ecuador in 545 fathoms. (See Appendix, No. 7).

SUMMARY OF KNOWN ENCOUNTERS OF WHALES WITH SUBMARINE CABLES

(1) Location. Eight cases between 13°N and 13°S along Pacific coast of America ; one case near Nova Scotia ; one case in the Persian Gulf ; one in Alaskan waters ; one off Cape Frio, Brazil ; one case from somewhere off the west coast and one case from somewhere off the east coast of South America.

(2) Depth.	Six cases about 500 fathoms ; three cases about 200 fathoms; three cases about 65 fathoms ; two unknown depths.
(3) Season.	Five whale carcasses were brought in during February, March and April ; two in July. Whale skeletons were found in August and December, but do not indicate the time of entanglement.
(4) Nature of Entanglement.	In most cases the cable was wrapped around the whale's jaw and around its flukes (Fig. 2). Some cases were reported when the cable was only wrapped around its flukes and some when the cable was only wrapped around the whale's lower jaw.
(5) Type of Whale.	All of those positively identified were sperm whales but those found in shallow water may have been baleen whales (GILMORE, 1955). A humpback whale has been reported caught in a cable in Alaskan waters (GILMORE, 1955).
(6). State of Preservation of Whale Carcass.	In seven cases the whales' carcasses were well preserved when brought up. In each of these cases the repair was made 2-7 days after the damage occurred. In one case in 30-70 fathoms the whale's carcass was partly decomposed after only two days and in another case in 70 fathoms decomposition was far advanced after two weeks. On two occasions only the skeleton was recovered, the body having completely decomposed.
(7) Type of Damage.	In only one case were the armour wires broken. In all other cases described the insulation was spewed out between the armour wires and in a few cases the conductor was broken.
(8) Type of Cable Damaged.	Damage has occurred in all three of the basic cable types, heavy, intermediate, and deep sea (light). The approximate (good condition) breaking strengths of these types are 20, 12, and 10 long tons, respectively.
(9) Cable History in the Locality.	In most of the cases the cable was damaged by whales at or near a former repair. This probably means that there was extreme slack in the cable at these points.

DISCUSSION

From a study of the reports (see appendix) it is clear that the whales caused the damage to the cables which necessitated these repairs. They became entangled at the sea floor and not at intermediate depths during the repair. The characteristic mauling type damage and the good correlation between number of days from failure to repair and the state of decomposition of the carcasses support this conclusion.

The possibility that the deep water entanglements involved dead whales transported by water currents, land slides or turbidity currents from shallow water can also be rejected on the basis of the evidence cited above. In addition turbidity currents forceful enough to propel a whale could certainly have broken the armour wires of the cable. Currents would not explain the mode of entanglement or the fact that no whale damage has occurred in depths greater than 620 fathoms.

The question of how the whale became entangled in the cable cannot be answered from the data presented here. However, the most plausible explanation is that as the whale skimmed along the ocean bottom in search of food it encountered the loops (Fig. 3) of an extremely slack cable. The whale may have caught one of these

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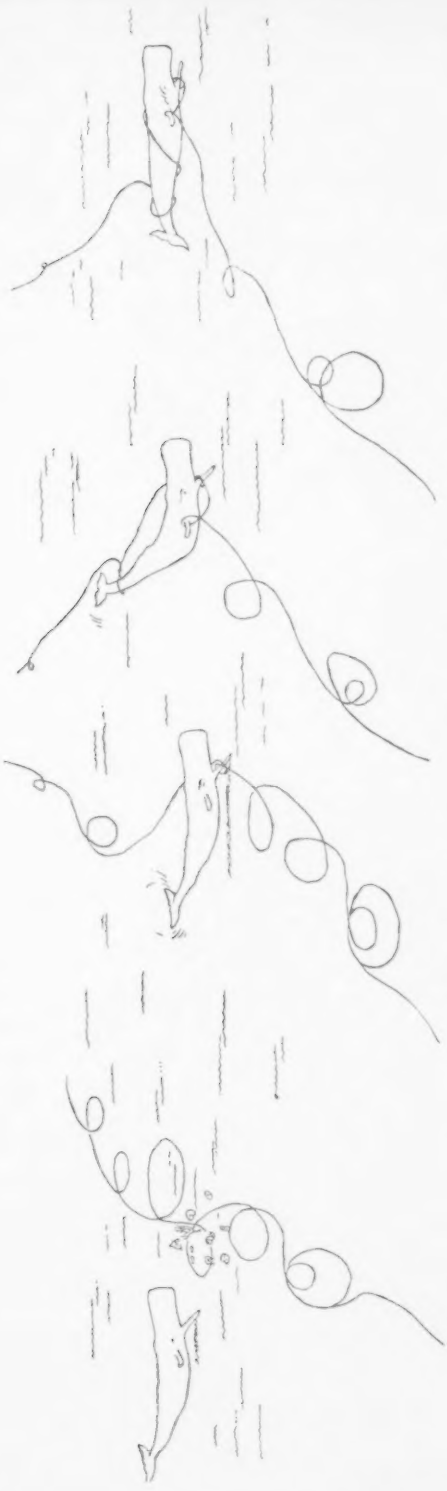

Fig. 3. Hypothetical sequence of whale entanglement.
Left. to right : 1. Whale skimming along bottom with lower jaw in sediment searching for food. 2. Whale gets lower jaw in loop of slack cable. 3. Whale struggles and gets fin and flukes in adjacent loops of cable. 4. Whale completely entangled dies on sea floor.

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loops in its mouth. Then as it continued to swim this loop tightened around the jaw and other loops tightened around its flipper and flukes as the cable was pulled tight along the whale's side. As the whale struggled the loops tightened so that the whale could not get loose. The whale bit the cable with its teeth and thus squeezed the insulation out through the armor wires, but the whale did not have enough force to break the armour wires of the cable (breaking strength 8-20 long tons). In a few cases the bite of the whale or the effect of its movements in the tightening of a kink was sufficient to break the copper conductor.

The occurrence of whale entanglements off the coasts of Ecuador and Peru in March may be related to the seasonal migration of sperm whales (TOWNSEND, 1935), but the number of reported occurrences is not yet sufficient for any firm conclusion.

The high occurrence of breaks at about 500 fathoms may be due to the natural occurrence of food at this depth. It may also be due to extra slack left in cables at this depth. On steep slopes it is difficult to determine the exact depth, and in order not to leave the cable under tension on the bottom, the cable ship masters may have laid out extra slack when engaged in repairs in these areas.

The writer does not pretend to understand the physiology of whales and how they can withstand such large changes in pressure. However, it now seems well-established that sperm whales often swim near the bottom in depths as great as 620 fathoms. It seems plausible that the whales become entangled in the submarine cables while swimming along in search of food, with their lower jaw skimming through the upper layer of sediment. It may also be that the whales attacked the cable mistaking it for prey.

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APPENDIX*

Reports of Whales Entangled in Cables

1. *Kurrachee (Pakistan) – Owadur Cable*

This cable was reported interrupted by a whale in 1877 or 1878 in a note published in the *Scientific American Supplement* for March 9th, 1878.

> " Mr. Isaac Walton, superintendent of telegraphs for Mekran and the Persian Gulf, reports as follows to the government at Bombay : ' The cable from Kurrachee to Owadur, about 300 miles long, was suddenly interrupted on the evening of the 4th inst. The telegraph steamer, Amberwitch, Captain Bishop, with the staff of engineers and electricians, under the orders of Mr. Hy. C. Mace, started next day to repair the fault, which was estimated to be 116 miles from Kurrachee, according to the tests taken from both ends.
>
> " ' The Amberwitch arrived at this place at two o'clock in the afternoon of the 6th. The sea was rough, and there was a thick fog at the time, but the cable was nevertheless hooked at a quarter of a mile from the point of rupture.
>
> " ' The soundings taken about the place of this break were very irregular, and showed a jump from 70 to 30 fathoms. In hauling in the cable an unusual strain was experienced, as if the cable had fouled, a rock, but on persevering for some time the body of an enormous whale, entangled in the cable, was brought to the surface ; it was found to be firmly held by two and a half turns of the cable, taken immediately above the tail. Sharks and other fish had partly devoured the carcass, which was rapidly decomposing, the jaws coming adrift on arriving at the surface. The tail, which was twelve feet wide, was perfectly preserved, and was covered with numerous shells at its extremities. Apparently the whale had rubbed itself against the cable for the purpose of ridding itself of parasites, and had with a stroke of the tail broken the cable, and, at the same time, so coiled itself up in it as to be strangled thereby.' "

*A Fault : A failure in insulation but with conductor continuity between the two terminal stations.
An Interruption : A complete rupture of the conductor severing all communication.
Nauts : Nautical Miles.

2. *Cable belonging to the West Coast of America Telegraph Company*

A cable belonging to this company was reported broken by a whale in a letter written to the (London) *Times*.

> August 14th, 1884, "A WHALE'S ADVENTURE"---"Sir: As a matter of curiosity and unique experience in connection with the working of submarine telegraph cables, I beg leave to hand you some extracts from the letters from our manager on the West Coast of South America and also from the Captain of our cable repair steamer.
>
> "Judging from the extracts, it would seem that the whale voluntarily attacked the cable, and having had a free fight with it, paid for his temerity with his life, for he was held prisoner for seven days and then mangled unto death.
>
> "The Captain of our repairing steamer writes :--'Having picked up 21 knots of cable, while continuing picking up, an immense whale came up to the bows entangled in the cable. It seemed to be about 70 feet in length. In its struggles to get free, the cable cut right into its side, the whole of its entrails coming out, and great streams of blood. In its last dying struggle it parted the cable on the bow sheaves and floated to windward of the steamer. The cable was twisted up in the form of a wire rope for about two fathoms, and in six different parts it had the appearance of having been bitten through sufficiently to stop all communication. There is no doubt the whale has been the cause of the interruption.'
>
> "Our Manager also writes : 'The cause of the breakage of the cable, as has been pointed out to you in Captain Morton's report, was a huge whale which became entangled in the turns of the cable, and was held prisoner for seven days ; the interruption was unfortunate, but it is, at least, satisfactory to know that the cable did not give way naturally, and that where picked up, the sheathing, yard and core were found to be in an almost perfect state of preservation, in fact, looked as good as on the day the cable was first laid.
>
> *August* 12 (1884) (Signed) *Robinson Kendal, Chairman*
> *The West Coast of America Telegraph Co.*
> *(Limited)*"

3. *Brazilian Cable*

> *The Nautical Magazine* (1900) reports : "The Brazilian cable indicated a fault, in 1892, at about 70 miles from the land, requiring an expedition for repairs. It is said that the carcass of a huge whale was found entangled in the cable. When brought to the surface the cable was discovered wound round the cetacean, and it had been twisted by him into a complicated system of knots while in his death struggle."
>
> Unfortunately no data as to depth or position were given.

4. *Rio de Janeiro Cable* (*Western Telegraph Company*)

The Electrical Review (Vol. 41, No. 1034, p. 382) of September 17th, 1897, carried the following note :

> "STRANGE CAUSE OF A CABLE INTERRUPTION" : "A correspondent writing from Rio de Janeiro under date August 25th, 1897, informs us that on August 22nd, whilst the telegraph ship NORSEMAN was engaged picking up cable off Cape Frio, she brought up a whale which had become entangled with the cable. The cable had not parted, but the conductor was interrupted. The whale had probably been there some two or three weeks judging by its condition, its head breaking off during the picking up. It had been much worried by sharks. It measured 14 feet across its tail. The depth of water there is 66 fathoms, soft mud and clay bottom. Latitude 23° – 17½'S, Longitude 41° – 40¼'W."

5. *Hammel* (*New York*) – *St. Pierre Cable*

On July 25th, 1919, this cable was interrupted along the west side of the Cabot Strait channel. The cable was repaired the same day. When the cable was brought to the surface it was found that "the body of a whale was tangled in the cable." The depth along the repair varied from 113 to 152 fathoms and the position was 46° 05'N, 58° 40'W.

6. *Cable belonging to All America Cable Company on Pacific Coast of South America*

In a letter to Mr. Wilbur G. Sherman concerning the March 1931 case (#7), A. Hyatt Verrill reported :

> " The sperm thus found entangled with the cable by Captain Harne was his second experience ; the other whale was found several years ago and was much larger, although so badly decomposed the repair crewe were forced to cut the cable and let the body go without getting close enough to examine it. That one also had its lower jaw entangled in the cable. Captain Harne is not certain about the depth in that instance but as he recalls, it was about 200 fathoms.

Reprinted from *New Bedford Standard* in the *Nantucket Inquirer and Mirror* April 9, 1932

Dr. Raymond Gilmore (1955) recalls that :

> " Dr. Austin Clark of the Smithsonian said that he received from Mr. Archibald Pender of the All America Cable Company a report of a sperm whale in the cable at about 500 fathoms off Valparaiso (Chile) sometime in the 1920's."

7. *Buenaventura (Colombia) Santa Elena (Ecuador)* 1882 *Cable*

This section became faulty on March 3, 1931, and was restored on March 10, 1931. A message from the *All America* stated :

> " Fault found at ten miles from yesterday's cut in position, caused by whale entangled in cable."

The position of the fault was given as latitude 1° 10′N, longitude 80° – 08′ 30′′W, depth 545 fathoms, about 15 nautical miles northwest of Esmeraldas.

The *New York Times* of April 26, 1931, published the following item :

> " WHALE CAUGHT IN CABLE DROWNS AT SEA BOTTOM
>
> BALBOA, C. Z., April 19 (1931). The record catch of the present fishing season, a ninety-ton whale, was made by Captain P. R. Harne of the cable repair ship All America while investigating the cause of recent interruptions in the service of the All America Cable Company's line between here and Esmeraldas, Colombia. The monster was hoisted from a depth of 3,000 feet off the coast of Colombia by the cranes and winches with which the cable ship is equipped.
>
> The whale was dead, having drowned, according to Captain Harne, when it became entangled in the cable. Captain Harne's theory, based upon similar experiences, is that the whale was feeding by scooping along the ocean bed. Digging too deeply in search of food, it picked up the cable, which snarled over its lower jaw. Then in turning over to free itself the whale wrapped the cable around its throat. Its frantic efforts to get free only tended to entangle it more completely in the cable, thirty fathoms of which was coiled around its body when brought to the surface.
>
> There were no marks to indicate that carnivorous fish had attempted to feed on the huge carcass of the creature. This is explained, according to Captain Harne, by the fact that the whale, protected by a heavy coat of blubber is able to withstand the high pressure of greater depths than other fish, which could not descend three-quarters of a mile to the bottom where the creature's body was moored to the cable.
>
> In order to free the whale it was necessary to cut the cable and splice in a new section. Once freed, the huge carcass drifted away."

In a letter to Wilbur G. Sherman concerning this incident, A. Hyatt Verrill reports as follows :

> " In a recent conversation with Captain Harne, he showed me your letters of last summer asking for details in regard to the whale he found entangled in a cable off Ecuador, South America. The whale was a sperm, about 45 feet in length, which had unusually large teeth and was a bull. There was a turn of the cable around the lower jaw, another around one flipper and still another around the flukes (tail). The cable was on the bottom at a depth of 540 fathoms off Esmeraldas, Ecuador, and it was necessary to clear the damaged whale's body by cutting the cable on each side and then splicing the cut ends to restore service operated by the All America Cable Company from Panama."

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Reprinted from the *New Bedford Standard* in the *Nantucket Inquirer and Mirror*, April 9, 1932

LAURIE (1933, p. 369), probably referring to this case, states :

> " A case was related to me in 1931 of a dead sperm whale which was found off the Peruvian coast entangled in a submarine cable which had broken at a depth of 500 fathoms. The mate of the cable ship, " All America," informed me that when the cable was hauled to the surface it was caught in the angle of the whale's jaws and a loop was twisted around the tail. From these observations it is probable that the whale became entangled in the cable while actively engaged, possibly in the pursuit of cephalopod."

8. *Balboa* (*Canal Zone Santa Elena* (*Ecuador*) 1913 *Cable*

Repaired in April 1932. The cable was brought to the surface off the coast of Colombia. Entangled in it was a dead 45 foot male sperm whale. The submarine cable was twisted around the lower jaw and was wrapped around one flipper, the body and caudal flukes. The cable was raised from a depth of 540 fathoms. This report was taken from Carson (1951). However, it has not been found in cable company records.

9. *Paita* (*Peru*) *Chorrillos* (*Peru*) 1882 *Cable*

On March 13, 1932, communication between Paita and Chorrillos was interrupted with tests placing the break about 77 nautical miles from the former station. Two days later the vessel started repair operations and hooked into the section. Log extracts state that after cutting in and picking up some 2 nauts, " a dead whale broke surface entangled with the cable, cable having a turn round lower jaw." (Position : Latitude 8°55′ 21″S, Longtitude 81° 18′ 09″W, depth 255 fathoms).

It is interesting to note on this occasion, as well as in (7), that while the armour of the cable was distorted and displaced it still held at the point where the whale, in its violent death throes, had spewed out the insulated core from under the lay of the steel wires. In (7), however, the copper conductor was not severed while in (9) the entire core, copper and gutta percha had parted.

10. *Chorrillos* (*Peru*) *Iquique* (*Chile*) 1927 *Cable*

This section was reported interrupted on February 21, 1933, with tests placing the trouble about 44·5 nautical miles from Chorrillos. Here again the repair pattern was similar to (7) and (9). The ship hooked into the line as indicated by tests and after picking up north for ·77 nauts a dead whale broke surface with bight of cable under jaw and around tail. (Position : Latitude 12° 46′ 48″S, longitude 77° 42′ 00″W, depth 442 fathoms). Once more the sheathing wires were holding fast with the core spewed out and severed.

11. *Salina Cruz* (*Mexico*) *La Libertad* (*San Salvador*) 1882 *Cable*

March 21, 1935, the above section was reported silent. As in (9) and (10) tests indicated a complete interruption. Unfortunately when this circuit was lost cable ship *All America* was otherwise occupied and could not proceed on its restoration until some two weeks later. On this occasion the cable had been completely broken by the antics of the whale (latitude 12° 58′ 36″N, longitude 89° 28′ 51″W, depth 68 fathoms) and after two weeks immersion decomposition of the carcass had commenced.

The following, which appeared in the *Panama America* 5/17/35, tells the story more graphically :

> " Despite the fact that corrosion is the usual reason for the destruction of the cables of the All America Cable Company, whales, too, play an important part in the wearing process.
>
> " According to the officers of the *All America*, the cable company's ship which is now in the Balboa drydock, a recent job on a cable which runs from Salina Cruz to San Salvador proved a whale of an undertaking. Having received word in the usual manner that a section of the cable in that area had parted, the *All America* sped to the place where they believed the repair job was to be made.
>
> " In the early evening of April 5, the break in the cable was located and the broken section was being lifted to the surface.
>
> " As the end was dragged up the cable became heavier instead of lighter. Suddenly with a loud splash the disintegrated body of a giant whale with the end of the servered

cable wrapped securely about it, broke the surface of the sea. It was not a hard job getting the cable unwound for the whale had been dead so long that it immediately broke off in pieces and floated away.

"The tropic sea was fragrant no longer and as the officers and crew of the cableship leaned over the side to gaze in silent wonder at the huge body of the unusual mammal they held their noses with diligence."

12. *Paita* (*Peru*) *Chorrillos* (*Peru*) 1882 *Cable*

This section again suffered whale trouble on July 26, 1940. As before tests gave indications that the cable had been completely interrupted. On July 30th repair operations were started. Once more the usual whale sequence followed. The ship hooked in, picked up towards the test location and, on reaching it a dead whale broke surface with one turn of cable completely around head and two around jaw. (Position : approximately, latitude 6° 23′S, longitude 81° 08′W, depth 470 fathoms). Up until the whale surfaced the armouring wires of the cable held but on maneuvering the vessel to cut away the carcass, too much stress was applied and the cable parted.

With the whale floating, and still firmly attached to the northern side of the cable leading to Paita, it was used as a mark buoy to establish a reference point from which to grapple and raise the line again. From this it is evident that, although foul of it, the whale did not sever the cable armouring.

Captain Hack's description of the mode of entanglement was sufficiently complete to allow the preparation of a drawing (Fig. 2a). A crewman of the *All America* took two pictures of a whale entangled in the cable (Figs. 4 and 5).

13. *Santa Elena* (*Ecuador*) *Chorrillos* (*Peru*) 1893 *Cable*

On December 30, 1944, while engaged in making a repair to this section the skelton of a whale's jaw was found foul, of the cable in latitude 9° 07′ 18″S, longitude 80° 00′ 30″W, depth 560 fathoms. This, however, did not cause the interruption.

14. *Santa Elena* (*Ecuador*) *Chorrillos* (*Peru*) 1893 *Cable*

This cable was reported faulty on August 10, 1955. On October 14, 1955, the Cable Ship *All America* repaired the fault. The captain made the following report :

"Jawbone of whale came inboard in bight of cable on Chorrillos end. Cable ridden and this was evidently cause of fault. Cleared whale bone and bight before splicing cable."

Position : latitude 09° 00′ 30″S, longitude 80° 06′ 31″W, depth 620 fathoms.

A photograph of the whale jaw and the damaged cable obtained from the captain by Mr J. H. F. Petch is shown in Fig. 6. This entanglement in 620 fathoms is the deepest ever reported.

REPORTS OF CABLE FAILURES POSSIBLY ATTRIBUTABLE TO WHALES

A. *Sidney* (*Australia*) *Nelson* (*New Zealand*) *Cable*

The Electrical Review **49**, 1251, 808 of November 15, 1901, carried the following note : "THE CAUSE OF A CABLE INTERRUPTION. A fault removed a few months ago from the Eastern Extension Telegraph Company's Sidney – Nelson section at as great a depth as 330 fathoms was found to contain a tooth firmly fixed in the core or interior portion of the cable containing the conductor, although it was protected by the usual sheathing of thick iron wires and outer coverings. An expert examination of the tooth proved it to belong undoubtedly to a shark, the exact variety of which could not be identified. Five species are known to exist in a depth of 300 fathoms, and one as deep as 500 fathoms."

B. *Malaga* (*Spain*) – *Lisbon* (*Portugal*) *Cable*. (*Cable and Wireless*)

This cable was repaired August 29, 1951 by the cable ship Mirror, 33·2 Nautical Miles from Lisbon in 700-1665 fathoms. The positions and depth given for the two splices are 38° 14′N, 09° 33′W, 700 fathoms, and 38° 09′N, 09° 35′W, 1665 fathoms.

Captain J. C. West's report states that : "The original defect was core breaks in original 1929 cable, at an unbelievably knotted tangle of bights caused by a large fish fouling cable. A one pound lump of soft, tough, amorphous fish tissue, highly oderiferous was tightly wrapped around the cable and subsequently cut clear with difficulty."

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Fig. 4. Photograph of a male sperm whale found entangled off Peru. Whale is floating in the water with the cable wrapped around its jaw. One end of the cable is on board the cable ship ; the other end extends to the sea floor. The photograph was made with slightly fogged film and has been slightly retouched. 30 July, 1940. (See Appendix, No. 12).

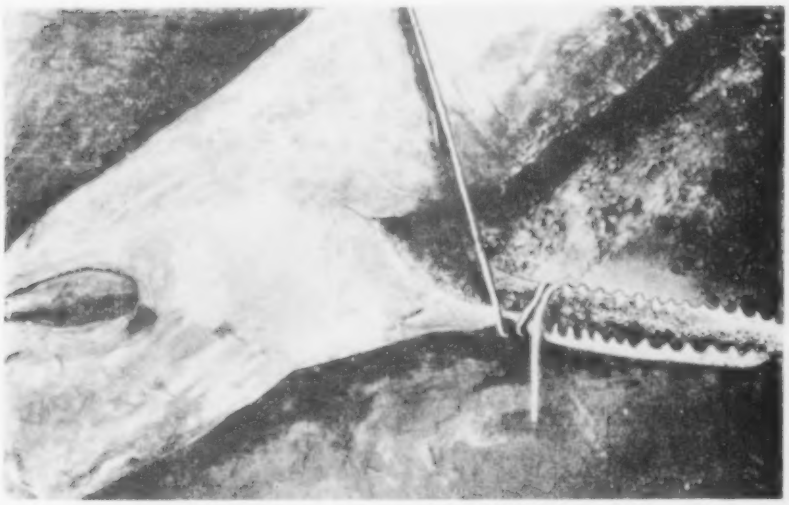

Fig. 5. Close up of same whale shown in Fig. 4 showing cable wrapped around whale's jaw and head. (See Appendix, No. 12). Depth 470 fathoms ; 30 July, 1940, off Peru. Photograph retouched slightly.

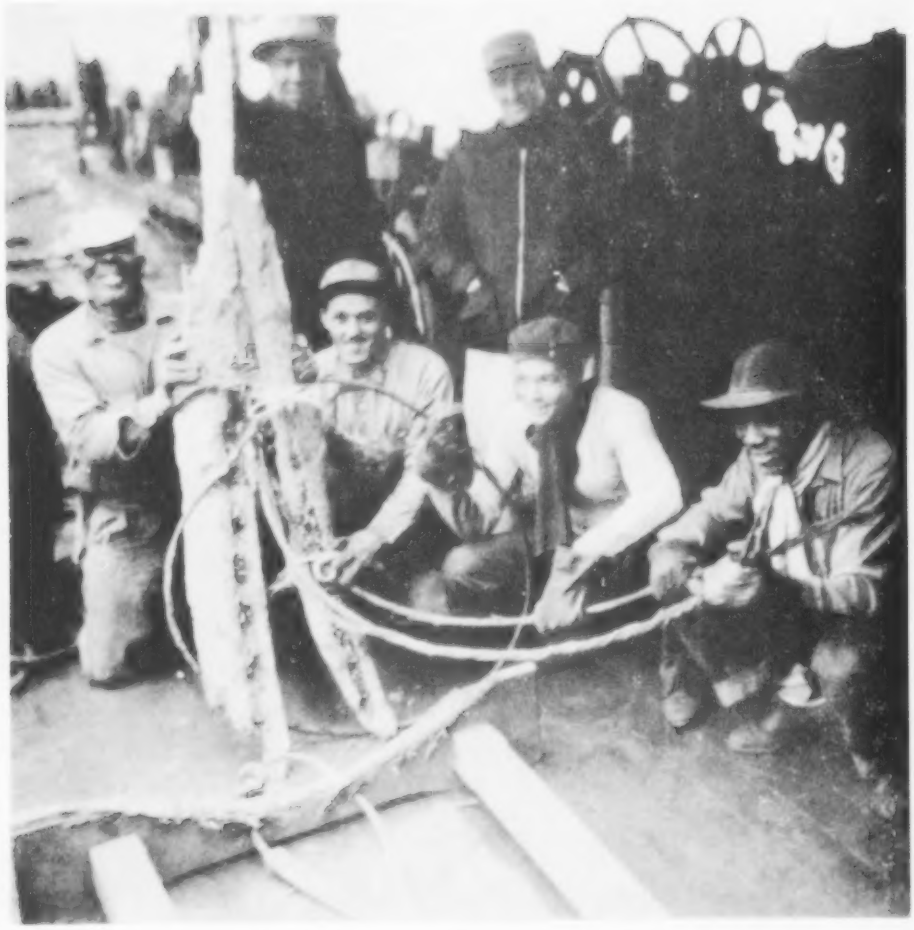

Fig. 6. Photograph of whale's jaw and mauled cable brought up from 620 fathoms off Peru on October 14th, 1955. (See Appendix, No. 14).

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The captain believed the depth (1200 fathoms) too great for whales and suggested the break was caused by an octopus. He concluded that the animal was large and powerful judging from the extent of the damage inflicted to the fairly new cable.

Acknowledgements—Professor MAURICE EWING called the writer's attention to the entanglement of whales in deep sea cables and encouraged him to undertake the present study.

Much of the information in the present report was supplied by H. J. ROSENBERGER, Assistant Chief Engineer, All America Cable and Radio Company, New York. C. S. LAWTON, General Plant Engineer, International Communications, Western Union Telegraph Company, provided information on the repairs of his company's cables. J. HACK and J. P. F. PETCH of the All America Cable Company gave a first-hand account of the 1940 repair. C. C. TAYLOR of the Commercial Cable Company provided additional details. REMINGTON KELLOGG, Director, and DAVID H. JOHNSON, Acting Curator, Division of Mammals, U.S. National Museum, provided helpful clues to published newspaper reports. R. J. MENZIES and R. BIERI of the Lamont Geological Observatory made helpful suggestions. RAYMOND M. GILMORE of the U.S. Fish and Wildlife Service read the manuscript and made several valuable suggestions. W. E. SCHEVILL of the Woods Hole Oceanographic Institution and G. E. R. DEACON of the (British) National Institute of Oceanography offered encouragement. HOWARD FOSTER assisted in searching cable failure reports and retouched the photographs. MARIE THARP drew the illustrations. The preparation of this paper was supported in part by the Bureau of Ships, U.S. Navy, under Contract NObsr 64547.

Lamont Geological Observatory
Columbia University
Palisades, New York

Contribution No. 234 *from Lamont Geological Observatory.*

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Television-echo sounder observations of midwater sound scatterers

RICHARD H. BACKUS and HAROLD BARNES*

(*Received* 30 *January* 1957)

Abstract—Simultaneous observations with echo sounders and underwater television have been made both in and out of deep scattering layers. All the evidence indicates that, with the type of sonic gear used, micro plankton was not responsible for either the observed deep scattering layer or for detectable echo sequences on the short range equipment. It was possible to " see " for the first time the sound scatterers responsible for the typical echo sequences from single animals and to confirm the deductions of JOHNSON *et al.* (1956) that individual small fishes give rise to the sort of echo sequences that have been seen in deep scattering layers. The type of echo record and its relation to the number of fish scattering the sound was observed.

INTRODUCTION

INDIVIDUAL animals both in and out of deep scattering layers have recently been resolved by the use of short range suspended echo sounders (JOHNSON *et al.*, 1956). Furthermore, using a camera mounted alongside the echo sounder, photographs were taken when strong echo sequences were being recorded in an attempt to identify the origin of the sound scattering. In these experiments images of fishes on the photographs were always accompained by strong echo sequences ; on the other hand strong echo sequences were not invariably accompanied by images of fishes and correlations with other types of organisms could not be established. Some of these uncertainties are without doubt due to the fact that the fields of view of the camera and echo sounder may not be identical ; this problem may be largely overcome if the approximate acoustic field is viewed directly and continuously. Such viewing is obtained if the camera is replaced by an underwater television unit. It has already been shown that plankton and fishes may be viewed and sometimes counted and identified by underwater television and some success has been reported in identifying the origin of traces on conventional echo sounder records (BARNES, 1955).

APPARATUS AND PROCEDURE

The television equipment has been described (BARNES, 1953). In some of the experiments a loose fitting canvas cover was fastened to the framework. A body of water at any level is therefore to some extent trapped so that movement of water past the window is reduced and the plankters are more easily recognized. The echo soundings were made with either an Edo UQN-1B (12 kc) transducer operating at the surface or a suspended echo sounder consisting of transmitting and receiving UQN-1B transducers operating at 34 kc. The Woods Hole Oceangraphic Institution precision graphic recorder (KNOTT and HERSEY, 1956) was used with both systems. The suspended echo sounder transducers were mounted on the gantry of the television camera and aimed at a point about seven feet away on the camera's optical axis.

*I wish to acknowledge both the receipt of a Research Fellowship from the Woods Hole Oceanographic Institution and leave of absence granted by the Council of the Scottish Marine Biological Association.

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The usual brass target ball (JOHNSON *et al.*, 1956) was hung below the camera also on the optical axis but at a distance of about nine feet. The depth of the equipment was determined either by echo-sounding from the surface or by a wire measuring device on the supporting cable.

EXPERIMENTS USING THE SURFACE ECHO SOUNDER

A strongly developed deep scattering layer as well as a zone of weaker scattering near the surface was observed on November 8th, 1956 at 39° 46′N, 70° 53′W in water of 920 fathoms (Fig. 1). The dominant layer was between 90-190 feet with its axis (level of strongest scattering) at 140 feet. Beginning at 00·10 hr the television camera with the canvas cover and two lights near the window was lowered by stages into the layer ; so rigged the observations relate primarily to plankton. At each depth notes were made from the screen picture and a series of counts taken by the method already described (BARNES, 1955). Between 40 and 230 feet many small copepods were seen (about the size of adult *Calanus finmarchicus*) and subjective estimates indicated little change in population density with depth. A number of euphausids were present at 120 feet. It was evident from the echo sounder record that with the lights continuously in use the intensity of sound scattering was reduced in the immediate vicinity of the camera. The lowering was therefore repeated (by which time the layer extended from 115 to 200 feet, axis 170 feet) but turning the lights on at each successive depth only for sufficient time to make a count. Each set of counts (70-100) took about five minutes during which time there was no evidence of any change in population density. The results are given in Table 1.

Table 1. *Mean number of plankters per count*, 8 *November*, 1956

04·20–05·00 hr		13·50–14·40 hr	
Depth (ft)	*No.*	*Depth (ft)*	*No.*
40	1·2	40	—
75	0·96	80	1·50
115	0·79	120	1·16
150	0·58	160	1·03
190	0·58	195	0·77
230	0·59	230	0·52

The results show that of the animals counted the greatest population density was at 40 feet ; there is no evidence that they were concentrated at the level of the scattering layer (115-200 ft) seen on the echo sounder unless the lights are considered to invalidate the results (see below for discussion).

The experiment was repeated during daylight on the same day at a position within five miles of the original observations ; by this time the deep scattering layer had migrated downwards and now lay between 960 and 1,680 ft with axes at 1,140 and 1,440 ft. The pictures appeared similar to those of the earlier experiment. The counts are shown in Table 1.

It is evident from this table that the population density and its relative distribution with depth was substantially the same for these small plankters during the night when the camera was within the deep scattering layer as during the day when the latter was well below the camera. This indicates that these small organisms were not

responsible for the migrating deep scattering layer observed on the echo sounder.

Although it was difficult to ascertain whether or not the lights affected the near surface scatterers it was evident from the echo sounder record that, as already pointed out, the intensity of scattered sound was reduced – presumably by repulsion or dispersion of the scatterers – as the lights entered the deep scattering layer. When the camera was well within the layer, switching the lights on and off gave a rapid and marked change in the echo sounder record (Fig. 2). That the small plankters counted on the screen remained constant under such conditions indicates even more strongly that they were not responsible for the observed scattering layer. Furthermore the speed at which the sound scatterers moved away when the lights were turned on suggests that larger, strong-swimming animals were responsible. This behaviour resembles closely that of certain fishes, (RICHARDSON, 1952).

EXPERIMENTS WITH THE SUSPENDED ECHO SOUNDER

These observations were made some 25 miles to the south of those described above, at 39° 22′N, 70° 52′W on November 8th, 1956 in water of 1,350 fathoms; a less well developed scattering layer was present between surface and 250 ft with its axis at 120 ft. The surface echo sounder was used only to check the position of the suspended echo sounder-television equipment with respect to the scattering layer, the echo sounder records being taken from the suspended unit. The television camera was rigged for full forward viewing with the whole complement of lights (2 kW) and without a canvas cover. Notes from observations of the television picture screen were entered on the echo sounder record and for part of the time a remote marker switch was operated by the television viewer to locate precisely the screen observations on the echo sounder record.

The observations extended from 20·30 to 24·00 hr during which time fishes and small plankters (mainly copepods) were seen. The last were present throughout the whole period and they never gave rise to detectable echo sequences. In contrast there was a high correlation between the presence of fish in the picture and a strong echo sequence on the echo sounder record. Although the correlation was high it was not complete. Occasionally fish were seen on the screen when either no echo or very faint echoes were recorded. As indicated by subsequent experience this was probably the result of imperfect alignment between transducers and television camera. On the other hand, the fishes were not specifically identified and therefore it is possible that some had no swimbladder and consequently low target strength. In contrast, echo sequences were occasionally obtained when fish were not recorded as present on the picture. This too may have been the result of misalignment but in this case the possibility that fish or other animals may have passed unobserved on the screen must be taken into account.

Most of the individual observations were of short duration, the fish image on the screen and the accompanying echo sequence usually lasting a few seconds. Of particular significance and interest was a set of observations in which a number of fish 3in.–7in. in length), probably in this case attracted by the light, swam in and out of the field of view for about forty minutes.

The echo sounder used can resolve individual targets only when their ranges differ by more than its ping length of about 0·2 milliseconds (about 1 ft). In these experiments one, two and three fish were individually resolved (Figs. 3–5). When a compact

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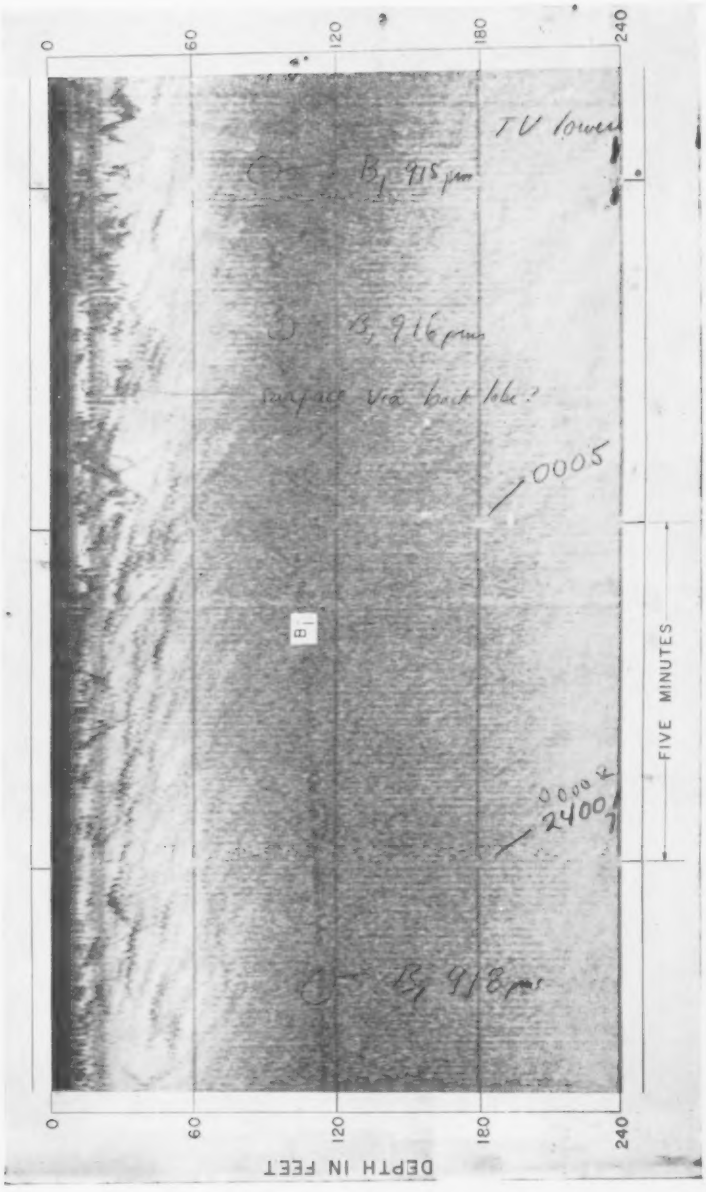

Fig. 1. Deep scattering layer near surface in 39° 46'N, 70° 53'W at about 00-05 hr. on November 8, 1956 before lowering television equipment. The bottom echo (B_1) is in a later interval and shows a depth of about 5,500 feet. A 16-foot correction (depth to transducer) should be added to indications of depth.

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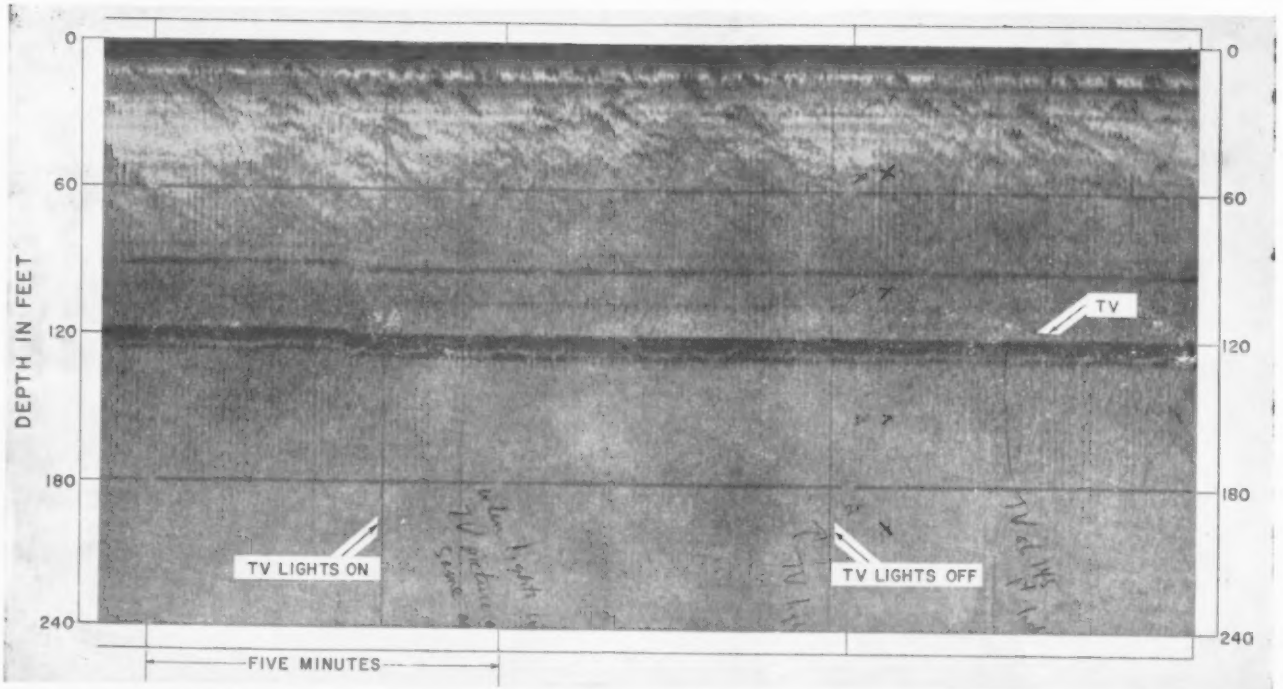

Fig. 2. Same layer as in Fig. 1 at about 01·30 hr. The disturbing effect of the television lights on many of the sound scatterers is shown. A 16-foot correction (depth to transducer) should be added to indications of depth.

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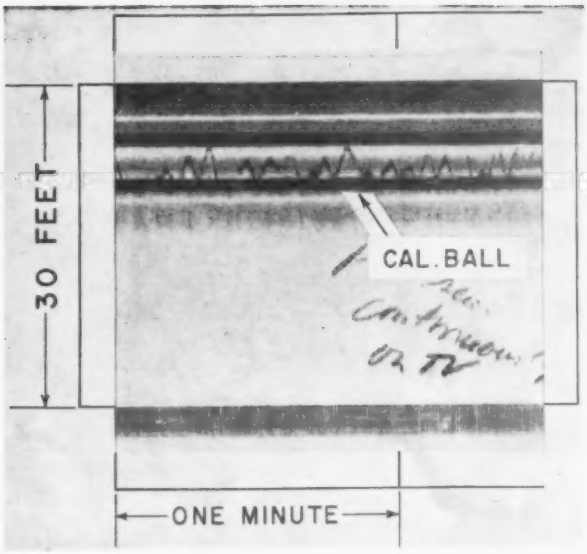

Fig. 3. Suspended echo sounder record made when a single fish was in view on television picture screen.

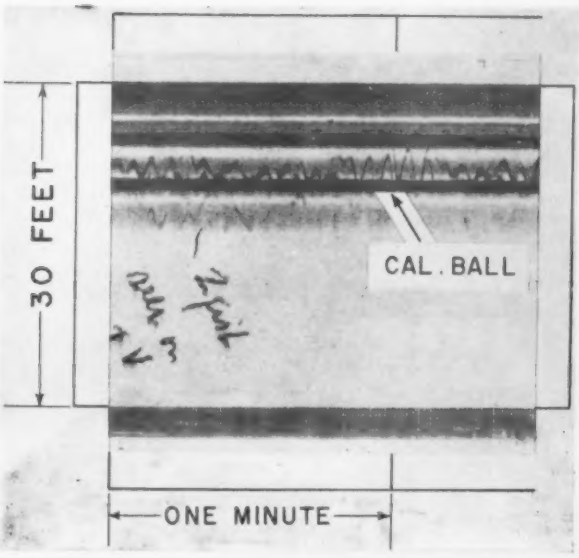

Fig. 4. As Fig. 3 but with fish in view on screen. Two echo sequences are discernible although much of one is obscured by the echo sequence from the target ball. A third echo sequence is discernible in the early part of the record at a range beyond that of the television camera.

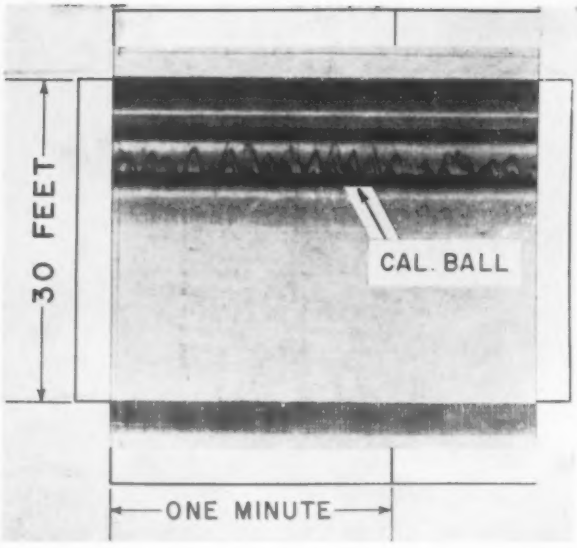

Fig. 5. As Figs. 3 and 4. 3 fish were viewed by the television and 3 echo sequences are discernible except when two or all fish are at same range.

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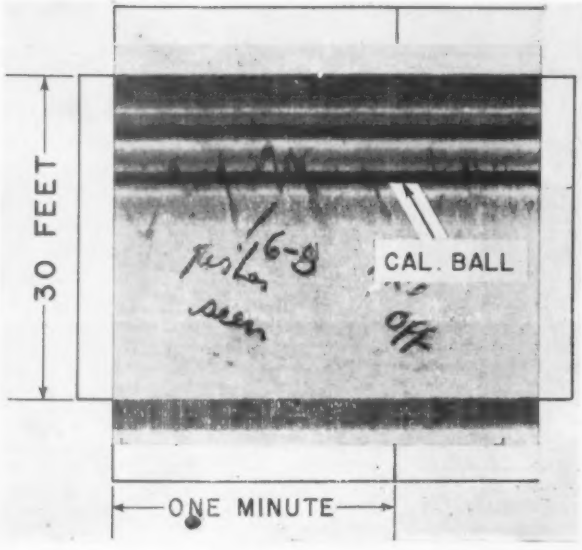

Fig. 6. As Figs. 3, 4 and 5 with 6-8 fishes present in a compact group. Individual fish are not resolved and a more complex echo sequence was produced.

group of 6–8 fish were present a single complex echo sequence was registered (Fig. 6) with continuous echo series whose length was greater than that of the ping. In such a case ; i.e., with several scatterers at the same or nearly the same range interference patterns (alternating maxima and minima in echo intensity resulting from phase differences) such as were seen by JOHNSON *et al.* (1956) might be expected. The absence of such interference patterns is probably to be explained by the fact that our recordings are overloaded.

The observations directly demonstrate that fishes give the type of echo sequence obtained by JOHNSON *et al.* (1956) using the short range suspended echo sounder in deep scattering layers ; small plankters at the population density present on these occasions produced no detectable echo sequences. We have no results as yet on other animals, e.g. squid, which have been proposed as the source of sound scattering in deep scattering layers.

DISCUSSION

These preliminary experiments indicate that television is useful in identifying the types and sizes of animals which produce strong echo sequences. Correlations between animal and echo sequence may be made. The establishment of such correlations is independent of any reaction of the animals to light so long as they are not completely repelled from the field of view. Observations may be made at any depth with either natural or artificial light and a picture built up of an organism-echo sequence correlation.

In spite of the reactions of the animals comprising deep scattering layers to light it is believed that further work on these lines would be valuable. The lights may be switched on only when observations are made when it is unlikely that all the scatterers will be completely repelled.

Acknowledgements—We are indebted to the officers and crew of *R/V Bear*, members of the underwater sound group at The Woods Hole Oceanographic Institution, particularly Mr. CHARLES S. INNIS, and Mr. A. G. RANDALL of The Marine Station, Millport, Scotland for their assistance. This work was done in part under contract NObsr–72521 with the Bureau of Ships, U.S. Department of the Navy.

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A new deep-sea underwater camera

A. S. LAUGHTON

Abstract—A deep-sea underwater camera containing several new design features is described. It is capable of taking up to a hundred pictures at one lowering in depths up to 5,000 m.

Some examples of its use in biological and geological surveys of the ocean floor are presented.

INTRODUCTION

OUR knowledge of the ocean floor has, until recently, been obtained by sounding, sampling and the measurement in situ of certain bulk physical properties such as density and elastic moduli. Many interesting features, however, can only be recognized by visual means and this is best done, if one has not the facilities of a bathscaphe, by remote photography or television. Although great advances have been made in the techniques of underwater television, it is still restricted to comparatively shallow depths.

In designing a deep-sea camera that is to be thought of as a tool, the guiding principles throughout were simplicity, ease of handling and flexibility in application. For these reasons, the camera was made as small as possible and all casings were made of light alloy so that it could be carried by two people and lowered on 4 mm hydrographic wire. 35 mm film was used so that it could be processed by standard techniques.

DESIGN

The three principal units which comprise the camera are the photographic unit, the electronic flash light and the acoustic signal generator or " pinger." The latter unit is necessary for transmitting the information to the surface that the camera has touched the bottom and taken a picture. The three units are mounted in a frame of aluminium alloy consisting of two lengths of scaffold tubing with spacers. The whole camera is eight feet long and one foot wide. The total weight in air is 87 lb (40 kg) and in water 41 lb (19 kg), (excluding the trigger weight). In normal operation the camera is actuated by the release in tension of a spring in the bottoming switch when the trigger weight and sampler touch the bottom. These are suspended beneath the camera so that pictures may be taken of the bottom at any given distance. The geometry of the camera assembly and the length of trigger line determine the focal settings and enable the size of objects in the field of view to be estimated.

The cases containing the photographic unit and the light unit are both mounted so that they can be pointed in any direction and can be interchanged in position. The electronics for the pinger unit are contained in one of the scaffold tubes forming the frame and the transducer and reflector point upward towards the surface. The whole assembly can be seen in Fig. 1, as it is being recovered after a station.

When taking photographs of the bottom, the camera is lowered until the bottoming signals are heard, and the first flash is triggered. (A picture is not normally obtained from this first touch of the bottom since the first frame has been exposed to daylight

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on the way down.) The camera is then raised a few fathoms and lowered again to take a picture after one or two minutes. This operation is repeated to give a series of photographs of the bottom while the ship drifts. A sample of the bottom (about 100 c.c.) is taken with a snap sampler when the camera first touches the bottom.

(*a*) *The photographic unit*

The photographic unit, Fig. 2a, was designed specially for the purpose and was required to fit into a 3 in. diameter tube. There is no shutter, the exposure being determined by the flash. After each picture has been taken, the film is transported automatically by an electric motor operated by 6-volt dry batteries. The time required for a new frame to come into position can be varied from 5 seconds to 1 minute by suitable gear selection. The camera wiring is shown in Fig. 3. On closing

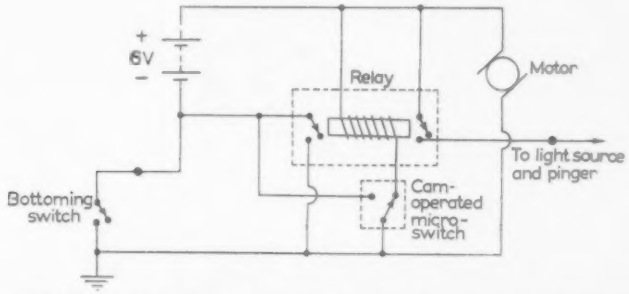

Fig. 3. Diagram of the camera circuit. In the rest state of the circuit, the bottoming switch and both relay contacts are open and the microswitch is made to the right. On closing the bottoming switch, the relay is energized and its contacts closed, triggering the light source and pinger, and shunting the bottoming switch. At the same time the motor is started and the film transported. After 3 seconds, the microswitch is switched to the left position by the film transport and the relay contacts open. After 12 seconds, a new frame is in position and the microswitch is switched to the right again. Provided the camera is off the bottom and the bottoming switch is open, the circuit returns to its initial state.

the bottoming switch, a 6-volt pulse triggers the light unit and the pinger and thereby takes the picture and signals to the surface. The film transport is operated until a new frame is reached when a cam-operated switch stops the motor. The film capacity is 5 metres equivalent to about 100 frames.

Two interchangeable lenses have been used, both Dalmac Anastigmat *f*/3·5 of 5·1 cm and 3·5 cm focal lengths. These cover an angular field of view in water of 37° and 47° respectively. The chromatic aberrations introduced by using underwater a lens designed for use in air, have been improved by the addition of a Thorndike correcting lens (THORNDIKE, 1955). This lens which is of zero mean power, but of finite dispersion, is mounted in the water in front of the window in the camera case.

(*b*) *The light source*

A low voltage operating repeating electronic flash unit is used for illumination. The power is supplied by nine 30-volt deaf-aid batteries in series forming a battery pack that plugs into the top of the flash unit. The circuit used is that recommended by the British Thomson-Houston Co. Ltd., for their 100 joule Xenon Tube F.A.10.

The charging time between flashes is limited by the internal resistance of the batteries and therefore depends on their age. With new batteries, 90 per cent of the full charge is reached in 40 seconds. The unit is shown in Fig. 2b.

A silvered reflector is used to spread the light as uniformly as possible over the area photographed.

(c) The pinger

The circuit for the pinger unit is shown in Fig. 4. This is essentially the same as that described by SWALLOW (1955), but with a modified repetition system. A ping

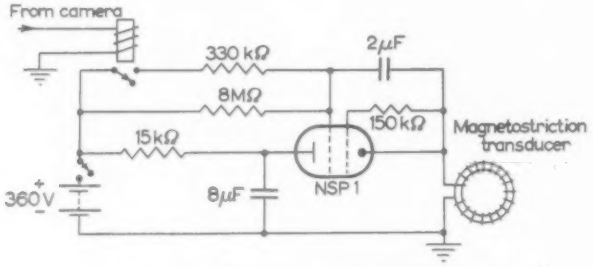

Fig. 4. Diagram of the acoustic signal generator circuit.

is transmitted every 6 seconds while the camera is in the water and can be heard through the hydrophone beneath the ship. When the camera triggers on touching the bottom, a lower resistance shunt is introduced in the repetition timing circuit and the pinging rate is increased to two a second. This high rate lasts for about 25 per cent of the time taken for the new frame to come into position, i.e. for about 3 seconds in normal operation when the film transport time is 12 seconds. If the camera is still on the bottom 12 seconds after triggering then the cycle is repeated and the winch operator is thereby informed that it must be raised further to clear the bottom.

The correct signals will be sent from the camera only if it is working correctly. It therefore gives great confidence to hear the correct signals and to know that all is well. In the event of anything going wrong, one can recover immediately and save not only time, but possible damage to the camera by prolonged immersion in water if a leak has developed.

The transmitted power from the pinger was found to be improved by a sonic reflector of $\frac{1}{4}$ in. (8 mm) aluminium plate. Under reasonably quiet conditions and using a directional hydrophone for listening it is possible to get clear signals from a depth of 4,800 metres.

(d) The bottoming switch

The bottoming switch, Fig. 6, consists of a microswitch operated by a cam on a spring-loaded shaft running through the switch unit. To the end of the shaft is attached the trigger line and trigger weight (which also incorporates the sampler). The switch unit is cased in Perspex and is oil filled.

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(e) The pressure cases

The cases for the photographic unit and the light unit are cylinders of aluminium alloy of 3 in. (7·5 cm) internal diameter and $\frac{3}{4}$ in. (1·9 cm) wall thickness designed to withstand 10,000 lb/sq. in. (700 kg/sq. cm.). The end caps screw into the cases and are sealed by trapped O-rings in the caps bearing on the flat end surfaces of

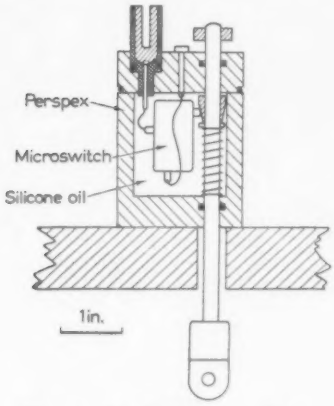

Fig. 6. The bottoming switch.

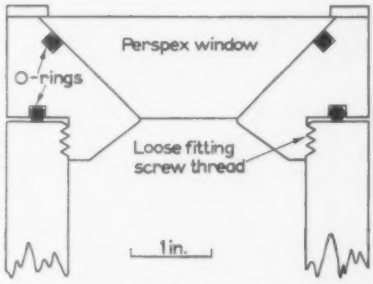

Fig. 7. The window end-cap of the camera pressure case illustrating the method of sealing.

the cylinders. It is essential, however, in this type of high pressure seal for the screw threads to be sufficiently slack to allow the pressure on the end caps to close the gap between the cap and the cylinder (Fig. 7). If this condition is fulfilled, then the cap need only be screwed on hand tight and the O-ring does not then suffer unduly.

The window for the camera is made of Perspex in the form of a truncated cone (Fig. 7). This fits accurately into a recess in the end cap and is sealed near the base of the cone by an O-ring. With this form of support, the distortion of the window under pressure is reduced to a minimum.

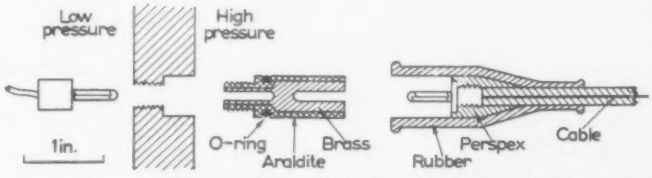

Fig. 8. An expanded diagram of the method of bringing electrical leads through a pressure case.

The flash tube is protected by a conical glass dome of $\frac{1}{4}$ in. (8 mm) thickness cemented by Araldite D cold-setting resin to the end cap. These Pyrex glass domes, which are commercially available for chemical use, have been tested in a pressure tank up to 13,500 lb/sq. in. (950 kg/sq. cm) without collapsing.

The scaffold tubing of aluminium alloy (HE 10 WP 1·9 in. O/D 7 gauge) forms the pressure container for the electronics of the pinger. The ends are sealed with plug type O-ring seals. Tests on the collapsing pressure of this type of tubing gave a

value of 8,700 lb/sq. in. (610 kg/sq. cm) which was somewhat less than expected. Because of this the depth to which the camera has been lowered was limited to 5,000 metres (equivalent to 500 kg/sq. cm).

Fig. 8 shows the method that is used to bring electrical leads through the pressure cases and how the connections are made. The centre part of the pressure plug is set in Araldite D and then machined. Mechanical support is provided by the brass centre and the necessary insulation by the Araldite. The seal to the case is made with an O-ring and the plug can be screwed in and out by hand. The outside connection to the pressure plug is made by a push-on rubber covered electrical plug. When the connection is made the air inside is virtually eliminated and the seal is made by the slightly extended rubber on to the Araldite insulation. This system enables the pressure plug to be changed in a matter of seconds if damaged, and the leads to be disconnected for testing. When tracing faults in the camera operation this is invaluable. The plugs have been tested up to 13,500 lb/sq. in. (950 kg/sq. cm) without any appreciable loss in insulation.

RESULTS OBTAINED WITH THE DEEP-SEA CAMERA

The camera has now been used on three separate cruises in R.R.S. *Discovery II*. In March and April 1956, preliminary sea trials took place in the neighbourhood of the Shetland Islands and the South Norwegian Sea. Seven stations were occupied but only three of these gave successful pictures, the failure in the other stations being due to the high turbidity in the water.

An opportunity for a more extensive test of the capabilities of the camera was afforded during the Geophysical cruise of July and August 1956, in the north-eastern Atlantic. Thirteen stations were occupied in depths of water varying between 110 metres and 4,824 metres. A total of two hundred pictures of the bottom was obtained. Of these about eighty showed bottom living fauna, the shallower stations in the vicinity of seamounts showing the greater proportion. At the majority of these stations a sample of the bottom was taken by the trigger sampler.

Since the photographic work in this cruise was an integral part of the other studies that were being made, a detailed discussion of the pictures obtained will be given in connection with the other results. However, a few of the more interesting photographs are reproduced here. (Figs. 9 to 13).

One picture, Fig. 13, demonstrated very clearly how much care has to be taken in the geological interpretation of photographs. This was taken near the top of a seamount 130 miles north of Madiera. When printed the picture showed broken boulders lying half covered with ooze. The boulders had clear markings on them in the form of parallel lines strongly suggesting bedding plants in a sedimentary rock. As this seemed unlikely, dredging was carried out at the same place and a boulder was recovered which bore similar markings (Fig. 14). These turned out to be corrugations on the cooling surface of a lava flow, the boulder being a highly vesicular basalt. On the bottom, the markings are probably accentuated by being filled with light coloured sediment.

In designing the camera, it was intended that it should be capable of adaptation to various underwater studies. An example of its use in midwater photography is described elsewhere in this volume (BAKER, 1956).

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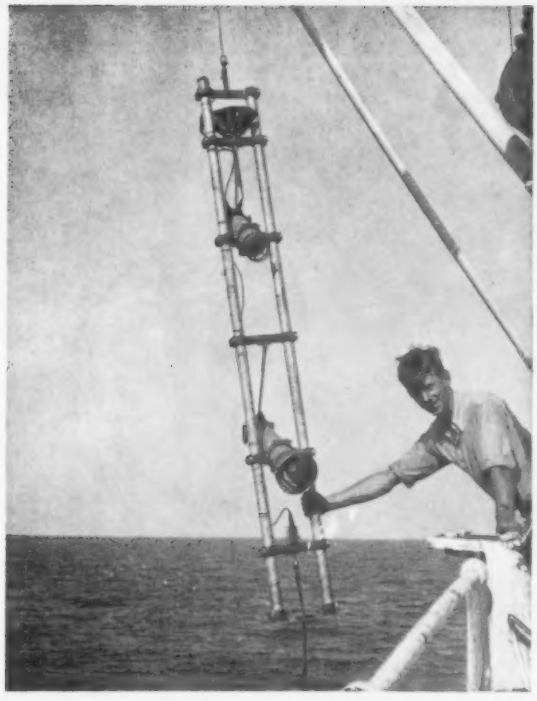
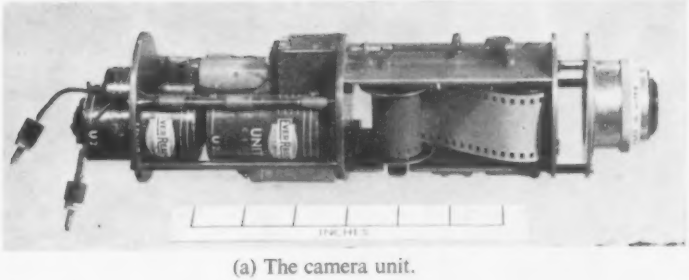
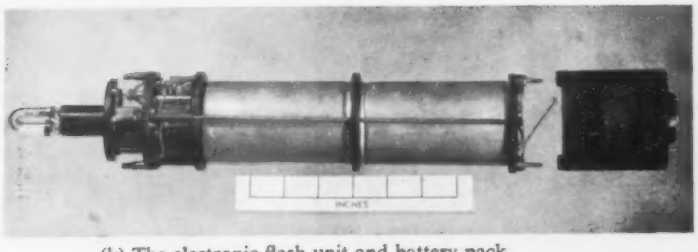


Fig. 1. The deep-sea camera being recovered after a station. At the top is the acoustic transmitter, below it the camera housing and near the bottom is the light source.



(a) The camera unit.

Fig. 2.



(b) The electronic flash unit and battery pack.

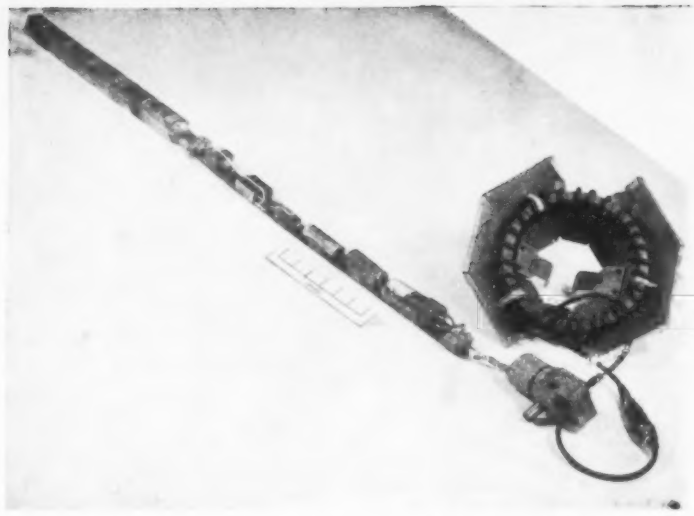


Fig. 5. The electronics and transducer of the acoustic signal generator circuit showing the reflector.

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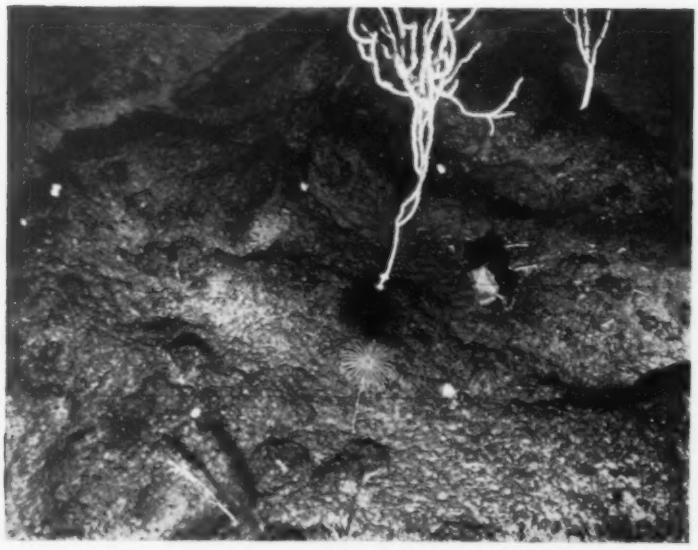

Fig. 9.
Station 3455.26. Position 34°53′N, 16°32′W. Depth 1,474 m.
Area of picture: 3 m by 5 m. Film H.P. 3: *f*/5·6: Range 5 m.
Outcrop of volcanic rock near the peak of a seamount north of Madeira. The lack of sediment cover suggests that currents are active. The fauna have been tentatively identified as follows: Chrysogorgid possibly *Isis* (top right): a Zeid fish possibly *Neocyttus* (middle right): a large Gorgonid or Anti-patharian (top centre): a spiralling Gorgonid related to *Iridogorgia* (lower centre): six sea anemones scattered on the rock.

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Fig. 10.
Station 3455.20. Position 34°53′N, 16°32′W. Depth 1,550 m.
Area of picture: 3 m by 2 m. Film H.P.3: *f*/5·6: Range 3 m.
The camera is looking into the slope on the side of a seamount north of Madeira. Loose boulders are lying half covered by calcareous sediments.

Fig. 11.
Station 3455.15. Position 34°53′N, 16°32′W. Depth 1,620 m.
Area of picture: 3 m by 5 m. Film H.P.3: *f*/5·6: Range 5 m.
Sediment lying in a depression on the side of a seamount north of Madeira. The marking on the surface may be due partly to current action and a resultant sorting of grain size and partly to the tracks of benthic fauna.

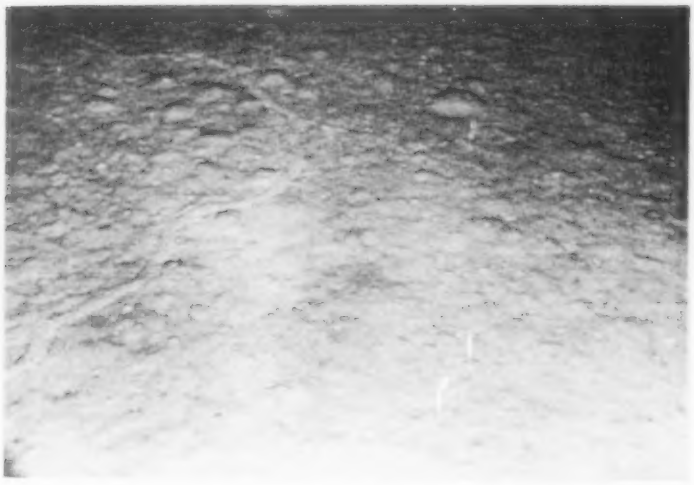

Fig. 12.
Station 3461.1. Position 36°36′N, 17°13′W. Depth 4,685 m.
Area of picture: 3 m by 5 m. Film H.P.3: *f*/6·3: Range 5 m.
Typical level bottom of globigerina ooze in the deep ocean basin north of Madeira. The many mounds are caused by burrowing fauna, possibly starfish. The track is probably due to a holothurian, producing footmarks separated by about three centimetres.

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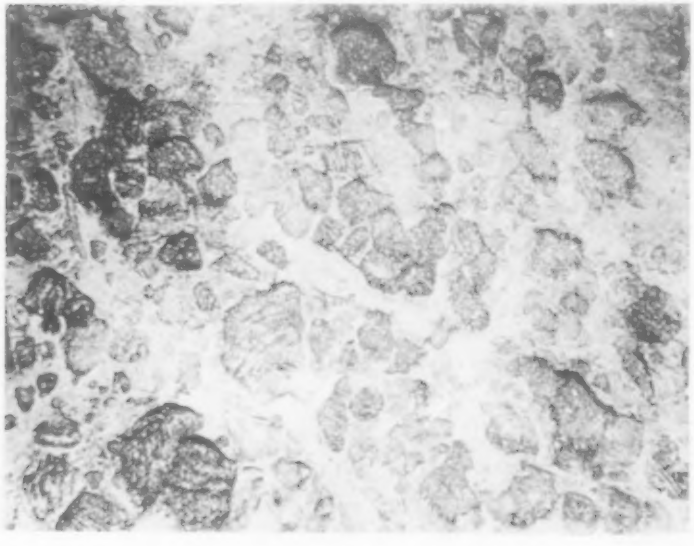

Fig. 13.
Station 3452.9. Position 34°52′N, 16°31′W. Depth 1,430 m.
Area of picture: 3 m by 2 m. Film H.P.S: *f*/11: Range 3 m.
The camera is looking into the slope on the side of a volcanic seamount north of Madeira. Loose boulders of vesicular basalt are lying half buried by sediment and pieces of broken coral. Note the striations on the boulders.

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Fig. 14. A boulder of vesicular basalt dredged from the same position as the photograph of Fig. 13. Striations can be seen, similar to those in the underwater photographs.

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Acknowledgements—The construction of the deep-sea camera was carried out at the National Institute of Oceanography. The author would like to thank Mr. R. DOBSON for his invaluable assistance in the design and preliminary trials of the camera, and also the Master and crew of R.R.S. *Discovery II* for their co-operation in conducting the experiments at sea. He is also grateful to Dr. T. F. GASKELL of the British Petroleum Company for permission to use photographs taken by him (Figs. 1 and 14).

National Institute of Oceanography, Wormley, Surrey

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Underwater photographs in the study of oceanic squid

A. DE C. BAKER

Abstract—A technique for photographing squid at great depths has been developed, which allows the species and size to be determined. Those photographed so far appear to be the same species as is commonly seen at the surface.

IN some recent short cruises of the R.R.S. *Discovery II*, attention has been given, among other things, to the populations of oceanic squid mainly in the region between the English Channel, The Azores and Gibraltar ; and the observations and material collected have provided some new information on their distribution. These studies have now received a considerable stimulus through the use of the deep sea camera designed by Dr. A. S. LAUGHTON and described by him in a separate article in the present issue of Deep Sea Research (p. 120). In a cruise in September, 1956, the camera was successfully adapted for photographing living squid in mid-water. MACKINTOSH (1956) has given a brief preliminary account of this work, but it may be useful now to give further information on the previous observations and to explain, with some technical details, the special value of the camera in these investigations.

Very little is known at present about the habits, distribution, numbers, or even the species of oceanic squid, but it is apparent that these animals must play an important role in the economy of the ocean both as prey and predators. The world population of squid must be extremely large, for they form the major part of the diet of sperm and other toothed whales, and in certain areas are also eaten by great numbers of seals and birds. From the observations of the *Discovery II* it is clear that they are plentiful everywhere in at least a large part of the North East Atlantic, for in these recent cruises they have nearly always been seen when lights are shone on the surface at night ; sometimes as many as twenty or thirty are in sight at one time. As predators squid feed mainly on fish and possibly other squid. *Ommastrephes pteropus*, the form commonly seen at the surface in this warm-temperate part of the North Atlantic, feeds to a great extent on garfish (*Scombresox spp.* which are extraordinarily abundant in the area covered), and also on the smaller Myctophidae.

The larger squid are very fast moving animals and are consequently rarely taken in nets of any kind. A wide variety of other methods of sampling the population has been tried. Large cage traps, spring loaded traps of various kinds, vertical long lines, towed lures, handnets and an ordinary rod and line have all been used at different times.

For taking the surface feeding *O. pteropus* the last two methods mentioned have been by far the most successful, as many as fifteen having been taken by handnetting in one night. Specimens up to an overall length of four feet or more can readily be taken by rod and line. Collections from the surface however, while providing material for systematic and anatomical work, provide very little information on their vertical distribution, a matter which is of particular interest. Sperm whales around the Azores are known to feed mostly on species of *Histioteuthis* and *Cucioteuthis*

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(CLARKE, 1956), yet these squid have never been seen at the surface during the cruises of the *Discovery II*. Further information about the vertical distribution of squid was obtained in 1954 in the Bay of Biscay when the arm of a squid was caught in a reversing water bottle at 1205 m. There is little doubt that this was from a species which has not been seen at the surface. This evidence shows that it is desirable to find some means of examining the populations in the deeper water layers.

Limited information about the deep-living squid has been obtained from the vertical long lines fitted with baited paternosters. These consist of horizontal rods three feet long with a two foot length of cod line, a short wire trace, and a triple hook, attached at one end. They are clamped onto the 4 mm wire used for working vertical plankton nets and are strengthened by a strut which is also clamped to the wire, and which supports the rod half way along its length. While the wire is being paid out any number of paternosters can be attached to it at the desired intervals. They have been fished from the surface to 2500 m during both day and night.

Although a squid has been caught by this method on only one occasion (an *O. pteropus* from 500 m), the baits, which are tied on to the hooks, have frequently been attacked ; this is indicated by the bait being completely removed, by marks of squid beaks on the bait or by suckers left on the hooks. Surface observations and the use of paternosters during recent cruises have given the impression that squid perform a diurnal vertical migration, rising towards the surface at night and descending during the day, but the data for the upper 500 m during daylight are not yet sufficient to confirm this.

The paternoster method has certain limitations. There must always be doubt whether, on every occasion that the bait has been taken, it has in fact been taken by a squid. This doubt does not arise when the bait bears marks of squid beaks, or suckers are found on the hooks ; even then, however, identification of the species is almost impossible. The limitations of the method also result in little or no information being obtained concerning the sizes and numbers of squid.

When the automatic underwater camera was developed it was suggested that, with suitable modification, it could be used to show the presence, size, and probably the species of squid at a particular depth. With this object in view an attachment was designed which triggers off the flash unit of the camera when a vertical downward pull is applied to the end of a pivoted horizontal bar similar to one of the paternosters referred to above. This is done by means of a micro-switch enclosed in an oil-filled waterproof casing. The amount of pull required to close the switch can be varied by altering the tension in a spring. The apparatus is attached to a short length of scaffold tube clamped below the normal photographic and flash units, and the whole instrument is fastened to the end of the 4 mm wire by a swivel. It will be seen from Fig. 1 that the positions of the photographic and flash units are the reverse of those used for bottom photography. During the first trials of the camera with the paternoster attachment, it was found that except in very calm weather, the movement of the ship caused a pull on the paternoster and as a result many blank photographs were taken. For this reason the adjusting spring had to be set to almost maximum tension. Another modification was the addition of a pressure switch which can be adjusted to trigger off the flash and wind on the film at a predetermined depth. Such a switch was necessary since the camera has no shutter and the first frame on the film is fogged owing to exposure on deck and in the upper water layers. It is hoped in the

future to incorporate a depth gauge in the field of the camera to provide permanent accurate depth records with each exposure.

In September, 1956 R.R.S. *Discovery II* was on station in position approximately 40°N, 20°W for two periods of a week each with an interval of a week when work was done in the vicinity of the Azores. During these three weeks the camera was lowered on fourteen occasions of which six yielded one or more photographs of squid. When the first successful photographs were taken the baited hook was set 12 feet from the photographic unit. Later, to improve the contrast on the negative this distance was shortened to 5½ feet. Also, since the squid photographed were only one to two feet in length, the wide angle lens (f.3·5 cm) was changed for one of longer focal length (f.5·0 cm) so that the squid filled more of the negative. The short trace wire was dispensed with and the hook was fastened directly onto the paternoster, thus ensuring that the bait and squid appeared in the centre of the field. This arrangement produced very much better results.

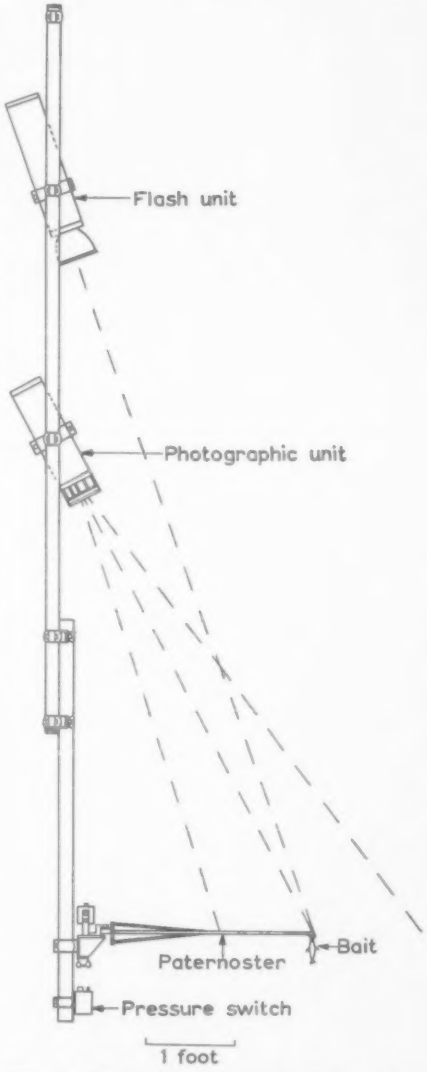

Fig. 1. The underwater camera fitted with the paternoster attachment.

Figs. 2 and 3 show five photographs of squid taken with the underwater camera at depths between 600 m and 1000 m with the modified system. A measure of the size of the squid is given by the marks on the paternoster which are at intervals of three inches.

Fig. 2 (a) shows the long body and triangular fin characteristic of the Ommastrephidae; also the angular membrane on the third arm can be seen clearly just below the paternoster. In Fig. 2 (b) the difference between the suckers of the long tentacles and the arms is apparent; the tentacle has two rows of large suckers with a row of smaller suckers on either side while the arms have just a double row of medium sized suckers. In Fig. 2 (c) the fins appear to be of a different form from that seen in Fig. 2 (a) and it is possible that this is another species. It seems more likely that the fins are being actively used for swimming and are in a position where the dorsal surface has been turned to face anteriorly. The squid has its ventral surface facing the camera and the siphon can be seen as the lower white mark above the arms.

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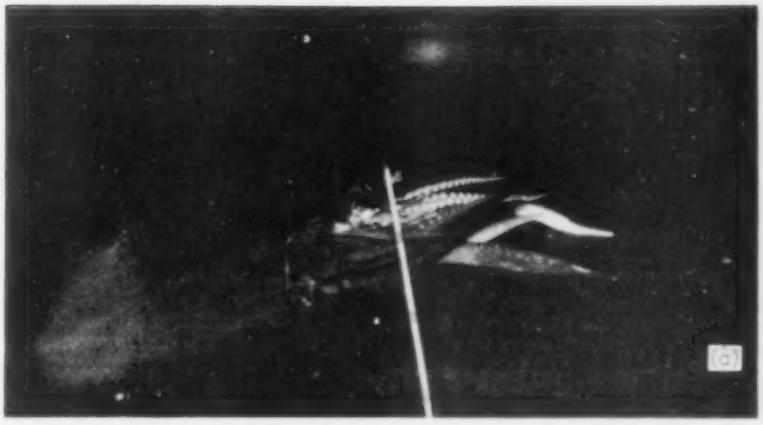


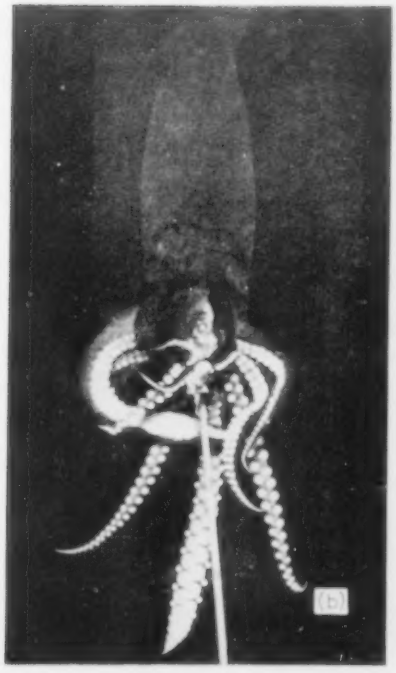
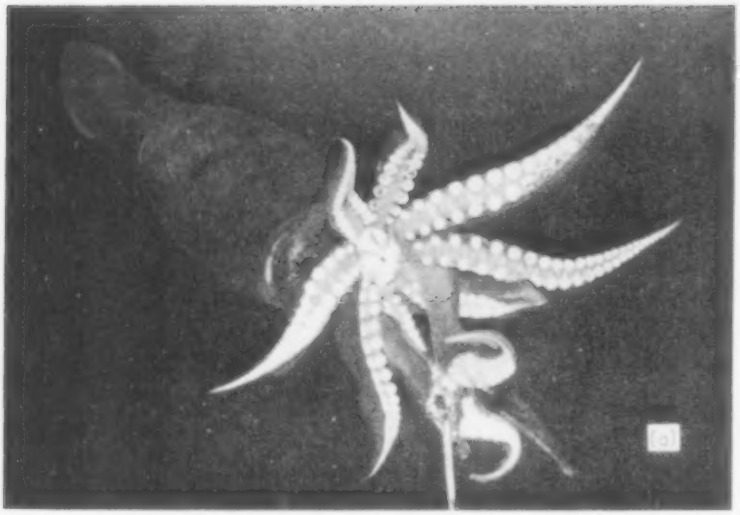


Fig. 2. Underwater photographs of oceanic squid.
(a) Station 3482, taken at 600 m.
(b) and (c) Station 3485, taken at 1000 m.



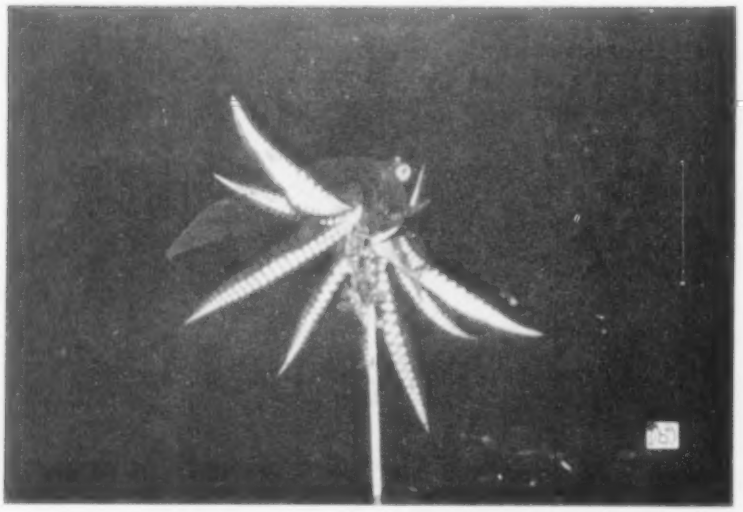


Fig. 3. Underwater photographs of oceanic squid. (a) Station 3484, taken at 700 m. (b) Station 3483, taken at 600 m.

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The whiteness is due to reflection from the lining of the siphon as the squid forces a jet of water out through it. (This can be seen clearly in Fig. 3 (b)). As the squid appears to have one arm caught on the hook, the position of the fins, the open siphon and the outspread attitude of the arms suggest that it is resisting an upward pull from the movement of the ship which would have caused the photograph to be taken. In Fig. 3 (a) the mantle cavity is very distended by water taken into it just before it is forced out through the siphon as a jet – a process frequently seen when squid are caught at the surface with a rod and line. The two tentacles are seen gripping the bait and the tip of the horny beak shows as a dark mark in the centre of the white buccal mass between the arms. In Fig. 3 (b) the whole head has been turned sideways and upwards to grasp the bait. The head of the bait is lying along the paternoster and the tail is held by one of the squid's arms. When the camera was brought to the surface the tail half of the bait had been removed.

All these photographs, with the possible exception of Fig. 2 (c), are probably of *Ommastrephes pteropus*. This species, which is found over such a wide area in the North East Atlantic, was observed and caught at the surface at the same time as the camera was recording it at 1000 m. Clearly it occurs in considerable numbers over a wide range of depth, and it would appear that, throughout this vertical range, *O. pteropus* is the dominant species of squid. It is, of course, possible that other species are less attracted to the garfish used as bait.

It may be possible in the future to modify the present underwater camera so that not only black and white, but also colour film or even a cine-camera, can be used. In any case it is likely to be developed and improved, and may have applications which cannot be foreseen at present.

National Institute of Oceanography
Wormley, nr. Godalming, Surrey

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Recent bathymetric charts and maps of the Southern Ocean and waters around Antarctica

H. F. P. HERDMAN

Abstract—Some recent bathymetric charts and maps of the Southern or Antarctic Ocean are discussed and some comparisons made between the various interpretations of the relief of the ocean floor. Reference is made to the nomenclature of features on the sea bed, and also to certain aspects of the continental shelf of Antarctica.

WITH the advent of the International Geophysical Year interest has again been aroused not only on Antarctica but on the waters which surround it. Recent new editions of exiting bathymetric charts and maps, and an entirely new map, have brought into prominence the amount of work already done – often under difficult conditions – to determine the relief of the bed of the Southern Ocean, and of the continental slope and shelf surrounding the continent.

Many authorities have contributed towards the knowledge which we now possess of the sea bed of the Southern Ocean. Much of it is still largely unexplored but there can be little doubt that it was the comprehensive oceanographical survey, begun here in 1925 by the former Discovery Committee, and continued later by the National Institute of Oceanography, which has produced a sufficient density of soundings to form the basis for the bathymetry of the charts and maps now under review. These fall into two quite distinct categories, i.e., that in which the primary object has been to contour a wide area of the ocean floor around Antarctica*† and that in which the delineation of the coasts and of known features on the Continent itself takes precedence‡§. In the latter charts, (or more correctly maps), depth contours have been drawn in at standard intervals for some distance seaward of the land, and the maps thus have an additional value in that features on the sea bed adjacent to or on the continental shelf can often be related to the topography of the continent itself.

On account of the long intervals of time which elapsed between the publication of the earlier editions of the bathymetric charts * † and the map ‡, and the great differences in the number of soundings plotted, any comparison between the various interpretations of the relief has not previously been considered, nor indeed, would it have been profitable. Now, we have not only a new (the 3rd) edition of the U.S.H.O. Chart No. 2562 of Antarctica, but an almost complete new edition of the International Hydrographic Bureau's Bathymetric Charts south of 46° 40′S (series B^1 and C^1). In addition, there is the recently published 2nd edition of the Australian map of Antarctica and the new *Karte der Antarktis*, recently published in Germany.

*United States of America, Navy Department Hydrographic Office, Washington, D.C., 1955. Chart No. 2562 (*Antarctica*).

†International Hydrographic Bureau, Monaco, 1952-55. Cartes Générale Bathymétrique des Océans, feuilles B^1_{I-IV}, $C^1_{II, III}$.

‡Map of Antarctica (1939) 2nd edition, 1956. Department of External Affairs, Commonwealth of Australia.

§HANS-PETER KOSACK (1955) *Karte der Antarktis* Geographisch-Kartographische Anstalt Gotha.

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All embody much additional information and, with the exception of one Monaco chart in the B^1 series published in 1952, all were published between 1954 and 1956.

The oceanic charts are on widely differing scales, and on very different projections. Chart No. 2562, for instance, is to the scale of 1 : 11,250,000 and on azimuthal equidistant projection, with soundings and depth contours in fathoms. The Monaco charts, on the other hand, are constructed on Mercator's projection between the latitudes of 72°N and 72°S (Series A, A^1, B, B^1), and on gnomonic projection for the polar regions (Series C and C^1). The Mercator charts are to a scale of 1 : 10,000,000 at the equator; those on gnomonic projection are to a scale of 1 : 3,100,000 at the parallel of 72°. Soundings and depth contours on the Monaco charts are in metres. Nevertheless, the density of soundings now is such that on the oceanic charts it is possible to compare the various conceptions of the features of the sea bed. There is little doubt that, even when the unit of depth is the same, the individual contours will vary – selection of soundings for plotting will account for some of this – but it is more likely that the main differences will result from the individual preferences of the cartographer or draughtsman. It has been said by one authority that if six draughtsmen were given an identical set of soundings to contour, they would produce six different interpretations. This statement is, possibly, a little sweeping, but there can be little doubt when one examines the charts and maps now being considered that, given the same data, there are wide differences in the conception of outlines of a number of features on the sea bed.

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The Australian Map of Antarctica ‡ and the German *Karte der Antarktis* § are again on different projections and to different scales. The first is an azimuthal equidistant projection and to a scale of 1 : 10,000,000 – the second is on Stereographic projection, to a scale of 1 : 4,000,000. Oceanic soundings and depth contours on both are shown in metres, but the smaller scale of the Australian map, with wider limits to seaward, makes it easier to relate oceanic features to the continental structure.

Gradation of colour in the normal manner is used to denote intervals of depth on the Monaco charts, and on the Australian and German maps. Contrary to this practice, which was followed in the two earlier editions, the new edition of U.S.H.O. Chart No. 2562 is not diversely coloured and is on a standard blue background; only the depth contours are shown. This is a retrograde step, and the value of the bathymetry would be very greatly increased were the normal differences in colour restored. Since this chart is not for navigational purposes but is purely a bathymetric chart, specially drawn to accompany the "Sailing Directions for Antarctica" published by the U.S.N. Hydrographic Office, it is hoped that despite the extra work involved it will be possible for the compilers of the next edition to revert to the original format.

A detailed comparison of these charts and maps is not possible in this paper ; it is however possible to draw attention to some rather outstanding differences in the delineation of a few of the better known features of the ocean bed.

THE BATHYMETRIC CHARTS OF THE SOUTHERN OCEAN AND THE WATERS AROUND ANTARCTICA. U.S.H.O. CHART NO. 2562 (3rd edition)

Many more soundings have become available since the last edition of this chart in 1947 and, in some areas, more especially the Pacific sector, the depth contours

now shown seem reasonably well established. It is interesting to note that in spite of the fact that on this chart there is no appreciable addition to the number of soundings, the connexion formerly suggested between New Zealand and Macquarie Island has been omitted. Reference was made to this by HERDMAN (1948), who suggested that there was a possible east-and-west exchange of deep water in this vicinity, between the Pacific and the Tasman Basin. Further hydrological observations in 1950 and 1951, by R.R.S. *Discovery II*, tend strongly to confirm this theory.

As already mentioned this chart shows the depth contours, without the normal gradation of colour with depth, and it is presumably on account of this that the names of major features of the ocean bed, such as ridges, basins, etc., have been omitted from this edition, whereas those of secondary features are inserted. It is also of interest to note that in spite of only a small amount of additional evidence by soundings some of the more legendary " islands " of the Pacific Antarctic sector shown in 1947 have been removed. For example, Emerald I., Dougherty I. and the Nimrod group are thus expunged although Swain's I. and Macy's I. still remain in spite of the evidence for their existence being equally doubtful. It is also rather surprising to see the retention of Thompson I. and the Chimnies (near Bouvetöya in the Atlantic sector). These were expunged from the British Admiralty Charts, by Notice to Mariners No. 406 in 1931, after an echo-sounding survey in the vicinity by R.R.S. *Discovery II* in 1930, and a flight over the whole Bouvetöya area by H. Riiser-Larsen from the research ship *Norwegia* early in the following year. The large number of additional soundings now available is, presumably, the reason for firm line depth contours throughout. In the earlier editions broken line contours were used where the interpretation was doubtful and, despite the additional soundings, this element of doubt should still persist in the deeper waters.

In spite of these criticisms of detail the chart as a whole remains a major and very valuable addition to our knowledge of the relief of the sea bed of the Southern Ocean.

I.H.B. CHARTS NOS. B^1_{I-IV} AND $C^1_{II, and III}$ (1952-55)

The Monaco bathymetric charts of the oceans and seas of the world are too well known to need explanation here and, like the U.S. chart mentioned above, they are not for navigational use nor are they intended to be more than a guide to the bathymetry of the sea bed.

Between the latitude of 46° 40′S and the Antarctic continent the Southern Ocean is covered by two series of charts, series B^1 between 46° 40′ and 72°S, and series C^1 between 72°S and the South Pole. Each series comprises 4 charts and, as in the earlier editions, considerable care has been taken to check the soundings supplied from various sources.

Depth contours have been carefully drawn in firm line to indicate that sufficient soundings are available on the original plotting sheets (there are 64 of these for each chart) to warrant a fair degree of accuracy in positioning the contours, and in dotted line where soundings are sparse. Unfortunately, in conformity with a decision of the International Committee on the Nomenclature of Ocean Bottom Features, only a small proportion of the soundings available from the plotting sheets are now inserted on the final charts. Where soundings are dense no doubt this is a wise decision, since with too many figures not only will there be a loss of the aesthetic value so long associated with the Monaco charts, but clarity will suffer. Nevertheless,

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the reduction, in sheet B^1_I, of the 28,282 soundings available on the large-scale plotting sheets, to 802 on the final sheet is too drastic. The proportion of soundings used in the later sheets (B^1_{II-IV}) of the 3rd edition has been increased considerably (from 2½ per cent to an average of 12 per cent), and in the C^1 series of the same edition it has been found possible to use 40 per cent of the available soundings in sheets C^1_{II} and C^1_{III}, without loss of clarity or aesthetic value*.

Throughout the oceans of the world there are few areas where the sea bed is level, and the Southern Ocean is no exception. When contours are shown in deeper water at 1,000-metre intervals the finer details of topography which are of importance to the geologists and geophysicists are sometimes obscured.

The policy, now being adopted by the International Hydrographic Bureau, of increasing the number of soundings on the more recent charts helps to meet this criticism, and it is hoped that it will eventually be found possible to include an even larger number of soundings. It would also be helpful to those studying the ocean bed in detail if some indication could be given where continuous lines of soundings have been taken, and for which echo records are available. This might be done by inserting a fine dotted line joining those soundings on the chart which belong to a continuous profile, or by a transparent overlay on which the continuous lines are marked. This latter method might not be satisfactory with sheets of this size. Finally, the lack of actual soundings makes it difficult to compare the relief of the bottom shown on the I.H.B. charts, with those charts or maps on which many more soundings have been plotted, and on which the interpretation differs.

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THE MAPS OF ANTARCTICA AND SURROUNDING WATERS

As stated earlier in this article the Australian Map of Antarctica and the German *Karte der Antarktis* are, primarily, maps of the Antarctic continent. Nevertheless, as will be seen from Fig. 1, the seaward limits of each map stretch into the Southern Ocean and the bathymetry of the sea bed to oceanic depths is shown in some detail. These maps thus help towards a better understanding of the relationship between the structure of the continental slope and shelf, and the structure of the continent itself.

MAP OF ANTARCTICA (1939), REVISED EDITION (1956)

The first edition of this map provides an extremely accurate representation of the coasts of Antarctica as then known and, in general, of the bathymetry of the surrounding waters. It was published in two sizes; one was a single circumpolar sheet to a scale of 1 : 10,000,000 and the other comprised two larger semi-circumpolar maps to a scale of 1 : 7,500,000. Lack of a 500-metre contour was rather a drawback, especially in the Ross Sea, though the few soundings shown here (HERDMAN, 1948, p. 92) made the omission not quite so obvious. The handbook which accompanies these maps contains much valuable historical information. In addition, it shows the care which has been taken to check not only the geographical data but also the validity of the soundings.

*The fact that all the reliable soundings available are first plotted on the large scale plotting sheets, and the contours then drawn before being transferred to the final chart is, of course, stated in the I.H.B. pamphlet which accompanies each new edition of the chart, as is the proportion of soundings finally used. Separate pamphlets become mislaid or lost, and there is nothing on the chart itself – other than the firm line contour – to show that other soundings may have been taken.

The new edition of the single circumpolar sheet just published shows the same care with regard to detail. Much new geographical information is included and many additional soundings have enabled the compilers to revise the bathymetry though, as in the earlier edition, the maps inset in the Pacific sector are rather a drawback when considering the bathymetry of the sea bed in this area. However, since the map

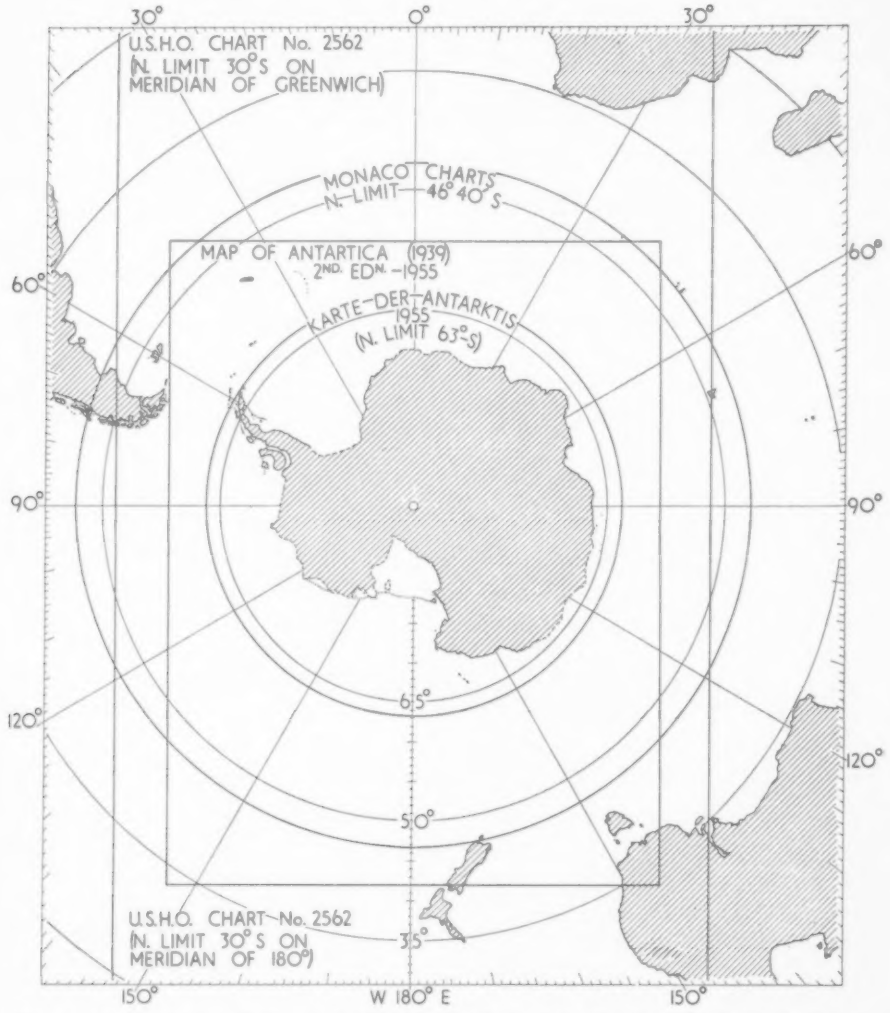

Fig. 1. Limits of some Bathymetric Charts and Maps of the Southern or Antarctic Ocean.

is primarily one of Antarctica, this criticism by an oceanographer is perhaps unwarranted. The inclusion of a 500-metre depth contour, together with additional soundings in the Ross Sea, gives a much more realistic conception of the sea bed here, but in the Atlantic sector it is a little surprising to find such a dearth of soundings

near the meridian of Greenwich, between 60°S and the continent. Many more soundings were taken here in 1938-39 by R.R.S. *Discovery II* and the German ship *Schwabenland*. These soundings show not only the extreme ruggedness of the bottom in this area, but indicate quite a different outline for the Maud Bank (more correctly Maud Seamount (HERDMAN, WISEMAN and OVEY, 1956)).

Generally, and as befits the high standard of accuracy set by the original compilers, the delineation of both major and minor features of the sea bed is as conservative as one would like to see where data are often sparse ; only very occasionally, for instance, are depth contours shown in firm line and then only when the density of soundings puts the matter beyond doubt.

KARTE DER ANTARKTIS, 1955

This map of Antarctica in four sheets by Dr. HANS-PETER KOSACK is, on account of its large scale (1 : 4,000,000), a valuable addition to the literature on the continent. Primarily, in respect of the continent itself, the map is of great geographical importance but, to the oceanographer it is also of value, in that depth contours are drawn for some distance north of the coasts. The map has a northern limit at the parallel of 63°S and within this area it is only between the meridians of 70° and 120°E that the depth contours do not extend to normal oceanic depth. Like the Australian map is it accompanied by a comprehensive booklet giving details not only of the sources consulted during the compilation, but also a full index of place names, together with their positions.

Generally, the depth contours seem reasonable and agree tolerably not only with those of U.S.H.O. Chart No. 2562, but also with the larger scale Monaco charts. Unlike the latter charts and the Australian map, no distinction appears to be made between depth contours which are well established and those for which the evidence is slender. There are, in addition, a number of depth contours, especially on the continental shelf between the meridians of 100° and 160°E, which are purely conjectural. Unless soundings were available which have not been plotted, evidence for these is not only slender but mostly non-existent. In the Pacific sector the 300-metre contour is shown stretching away in a narrow tongue to the north-west from, approximately, 70°S 130°W to, approximately, 62½°S 143°W. From the evidence of the soundings plotted the existence of a continuous ridge here is decidedly conjectural, and if reference is made to sheet B^{1}_{II} of the 3rd edition (1955) of the Monaco charts, it will be seen that, although there is some evidence of such a ridge stretching away in a north-westerly direction, it appears to be broken in places by deeper water. Reference to a Discovery Report on soundings (HERDMAN, 1948) would also have shown that there is very little likelihood of the Barth Bank (to the south-east of the South Orkney Islands) being included in the Scotia Arc.

NOMENCLATURE OF THE FEATURES OF THE BOTTOM RELIEF

As the result of the work of the International Committee on Ocean Bottom Features, and its national sub-committees, much agreement has been reached on the nomenclature of the types of features – both main and secondary – which constitute the relief of the ocean floor (WISEMAN and OVEY, 1953). Recommendations have also been agreed generally with regard to naming newly-discovered features and the British National Committee on the Nomenclature of Ocean Bottom Features has

recently published (HERDMAN, WISEMAN and OVEY, 1956) a list of proposed names of features of the deep-sea floor of the Southern or Antarctic Ocean.

Since there is fair international agreement on this subject, especially in connection with the major features of the sea bed, it seems a little unfortunate, but perhaps understandable, that the new edition of the Monaco charts does not carry the names of any feature, and that, contrary to the practice in the earlier editions of naming all features, only those of secondary features are now included in the new edition of U.S.H.O. Chart No. 2562.

Secondary features only are named in the Australian Map of Antarctica – though it would have been possible to have included some of major importance as, for instance, the Scotia Arc and the South Sandwich Trench. With a northern limit of 63°S no major feature of the bottom relief of the Southern Ocean is included in the Karte der Antarktis ; secondary features, however, are shown and named, although in many cases their geographical limits considerably exceed those usually accepted.

THE CONTINENTAL SHELF OF ANTARCTICA

In 1939 echo-sounding runs made by R.R.S. *Discovery II* from deep water up the continental slope of Antarctica, near the meridian of 4°E, showed that here there was virtually no continental shelf in the sense generally understood (HERDMAN, 1948). This information, in conjunction with such other data as was then available, led to the assumption that between this line and the meridian of 60°E the continental shelf was almost completely absent. Soundings by the German ship *Schwabenland*, now published in the *Karte der Antarktis*, confirm the initial absence of a continental shelf between the Greenwich meridian and that of 5°E, and the additional soundings now available to the eastward show that there is little or no indication of a shelf as far as 70°E.

Since the previous review of the extent of the continental shelf around Antarctica a number of additional soundings is available in localities other than those just mentioned. These show that eastwards of 70°E, and as far as Budd Coast, where it apparently again disappears, there is a recognisable continental shelf, though narrower perhaps than generally found around other continents. There are few soundings off Sabrina and Banzare Coasts and it is not until west of Cape Goodenough that the shelf is once more established. From here it runs westwards to the Ross Sea, with a considerable extension seawards between 150° and 155°W. The shelf narrows again at the western tip of Victoria Land and then spreads out across the whole width of the Ross Sea to Cape Colbeck. Here, the bottom again rises abruptly to a narrow shelf, which continues west to the meridian of 145°W.

The so-far impenetrable pack ice of the Pacific sector has prevented any near approach by sea to the continent. Soundings obtained along the ice edge suggest, however, that there is a wide continental shelf between the meridian of 145°W and Graham Land, except off the Thurston Peninsula, (longitude 100°W), where it narrows to 30 miles in width. The existence of a reasonably wide shelf off Graham Land itself was established by numerous soundings taken by R.R.S. *Discovery II* and *William Scoresby* some years ago. There appears to be little additional information off the South Shetlands, where a moderately narrow shelf prevails, and along the east coast of Graham Land (in the Weddell Sea). Impenetrable pack ice is again the reason for this but further to the west and south there is fairly good evidence that a

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wide shelf extends north to the latitude of 72°S. In approximately the longitude of 42°W it is interesting to note that there appears to be a break in the shelf. Three soundings, each exceeding 1,000 m. (547 fm.) are shown on U.S.H.O. Chart 2562, and on the *Karte der Antarktis*, which might – although the evidence is very slender – indicate a gully or trough leading up to the land. The shelf again narrows along the eastern coasts of the Weddell Sea and continues thus until it reaches the meridian of Greenwich.

National Institute of Oceanography, Wormley, Godalming, Surrey

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Virgin Islands bathymetric survey*

ROBERTO FRASSETTO and JOHN NORTHROP

(*Received* 1 *February* 1957)

Abstract—A bathymetric survey in the vicinity of the Virgin Islands showed that Anegada and Jungfern Passages, which connect the Atlantic Ocean with the Caribbean Sea between the Virgin Islands Platform and St. Croix Island, are the deepest charted passages between the two seas. The 1,072-fathom sill depth of Jungfern Passage is the limiting factor in the exchange of deep water between the Atlantic Ocean and the Caribbean Sea.

Furthermore, it was found that the Virgin Islands Basin, which lies between Anegada and Jungfern Passages, has a flat floor 2,400 fathoms deep. It is bounded on the north and south by sea scarps having apparent slopes of 9 to 43 degrees. The eastern end of the basin is divided into two arms which embrace a 420-fathom sea knoll. Both these arms terminate at sills which separate them from Anegada Passage and St. Croix Basin. The western end of the basin is connected with a smaller basin, 2,200 fathoms deep, which is bordered by Jungfern Passage on the south and by Grappler Bank on the west.

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INTRODUCTION

THE purposes of this survey were to determine the sill depths of Jungfern and Anegada Passages and to determine fairly accurately the bathymetry of the basin which lies between the Virgin Islands Platform and the St. Croix Platform. Sill depths have been critical in discussions of the exchange of water between the Atlantic Ocean and the Caribbean Sea (DIETRICH, 1939; WORTHINGTON, 1955).

Numerous geologists have discussed the bathymetry of the Virgin Islands Basin† (KEMP, 1927; MEYEROFF, 1927; SCHUCHERT, 1935; and CEDERSTROM, 1950). These earlier workers indicated that Puerto Rico and all the Virgin Islands formed a single unit in the Upper Cretaceous and the Lower Tertiary, and that post-Miocene fracturing and block-faulting separated St. Croix from the northern islands. The sharp boundaries of the basin, which are very steep particularly north of St. Croix and south of Vieques, support this thesis.

Seismic refraction data have been obtained in the area by C. B. OFFICER and R. S. EDWARDS (personal communication) and gravity measurements have been made (SHURBET, *et al.*, 1956). Their results indicate that sediment about 10,000 ft in thickness underlies the floor of the Virgin Islands Basin. Also, the thin section of crustal rocks under the basin, deduced from the gravity measurements, suggest extension of the crust (SHURBET *et al.*, 1956).

The detailed soundings shown in this report indicate that the floor of the Virgin Islands Basin is flat and that the topography is masked by sedimentation. They also indicate that the depth of Jungfern Passage Sill is of the order of 1,000 fathoms rather than 2,500 fathoms as reported previously (H.O. Chart 5487; HEEZEN in WORZEL and EWING, 1954, Fig. 1).

* This work was supported by the Office of Naval Research.

† Using the term " basin " as defined by WISEMAN and OVEY (1954), the name " Virgin Islands Basin " has been approved for this feature by the British National Committee on the Nomenclature of Ocean Bottom Features and by the U. S. Board on Geographic Names.

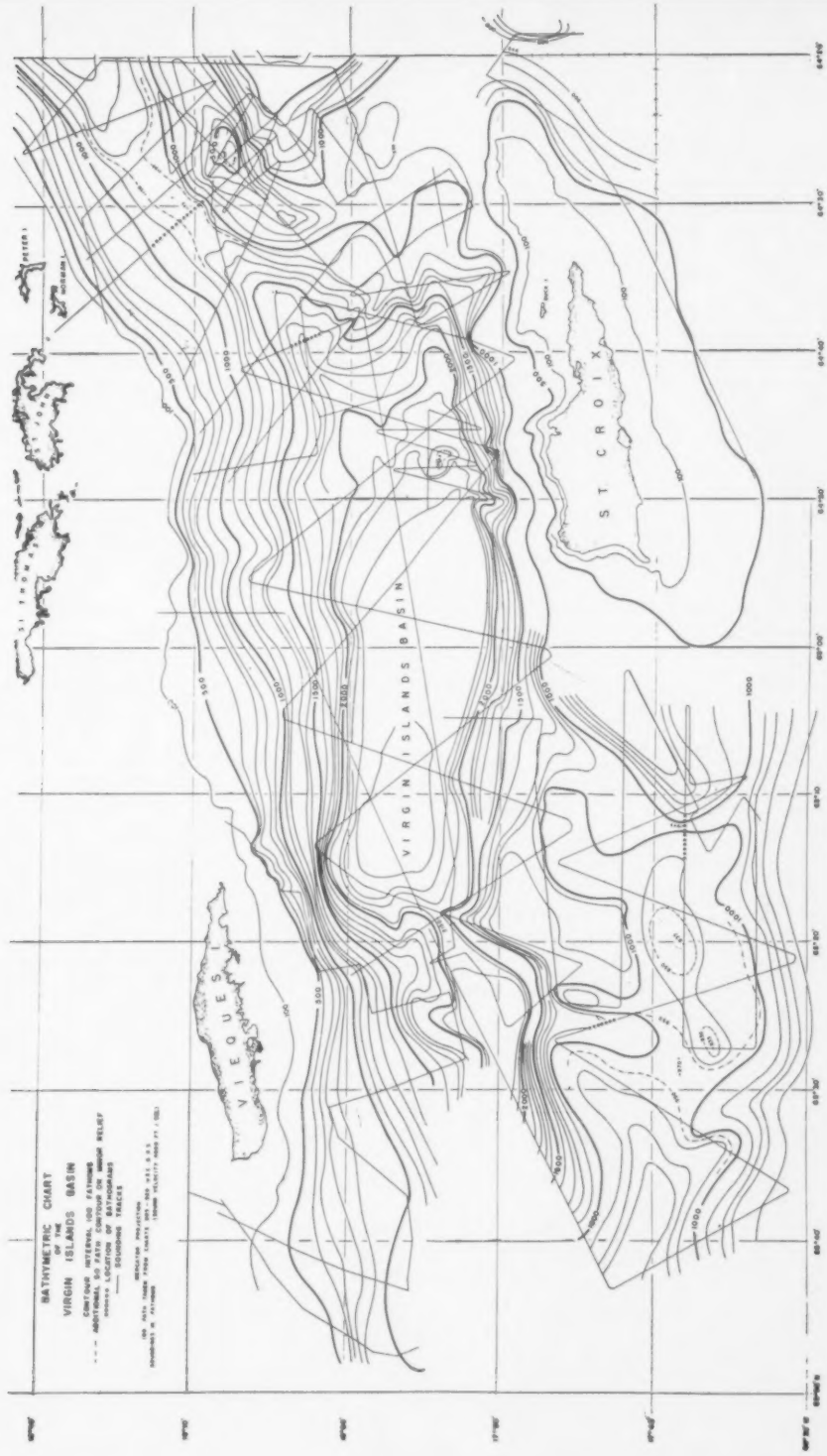

Fig. 1. Bathymetric chart.

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METHOD

The bathymetric surveys described in this report were carried out in the course of two cruises. The first, in the spring of 1955, outlined the major features of the Virgin Islands Basin. The second, in the spring of 1956, showed details of the eastern area of the basin, a sea knoll, and the sills east and west of St. Croix. Soundings were made with a continuously recording Edo sonic sounder (A/N UQN-1B) modified to record on an expanded scale introducing the third pen (NORTHROP, 1953). The ships' positions were obtained by bearings and radar ranges taken every 15 minutes and before and after each change in course, whenever possible. Because of the proximity of numerous islands on both sides of the basin, navigation by this method was particularly effective and ships' positions are believed good within 500 yards in the limits of land sight areas, and approximately one-half mile otherwise. The soundings for the first survey were made with the Edo operating on a 60 c.p.s. a.c. precision power supply and should be good to 1/10 of 1 per cent. During the second survey, no precision-cnontrolled alternatig current supply was available, but a check was made on the frequency meter at regular intervals and the meter proved to be quite stable. Corrections have been made in the cases where the frequency had to be stabilized. For all data, the readings are believed accurate within 1 per cent.

Depths were plotted at five-minute intervals as the survey progressed and additional readings were made during periods of four to eight hours while the ship was drifting. The plotting was rechecked and details added after returning to the laboratoıy. A contour map drawn from the data is presented in Fig. 1. All depths are sonic soundings based on the standard sounding velocity of 4,800 ft/sec. Corrections for true depth were made only at pertinent points.

An attempt was made to get an approximate idea of the true depth of the Jungfern Passage Sill* and of its width at the bottom (Fig. 2, Echogram Y). To construct the configuration of this sill, corrections for sound velocity were made from temperature and salinity data obtained from the Woods Hole Oceanographic Institution, *Atlantis* station No. 5286, 14-15 March, 1955, Lat. 17°53′N, Long. 65°18′W, approximately 15 miles north of the sill at depths from 0 to 3,820 metres. It was assumed that at the sill location temperature and salinity were approximately the same. The mean sound velocity from sea level vs depth was plotted and the correction added to the recorded depth to obtain the true depth was derived from it.

By applying a 2·6 per cent correction, which corresponds to the recorded depth of 1,045 fathoms, the corrected sill depth of 1,072 fathoms is obtained. This depth should then be accurate within 1 per cent due to the 60 c.p.s. a.c. current fluctuating plus or minus 1/2 to 3/4 of a cycle. (According to TOLSTOY and EWING, 1949, one cycle would give 1/60 of true depth error. Thus 0·75 cycle will give a 12-fathom error. Deducting one fathom for keel depth of the survey ship, one gets 11 fathoms, or 1 per cent of 1,100 fathoms.)

The width of the sill depth was calculated by obtaining a solution for the effective width of the base of the cone of sound at that depth (NORTHROP, 1953) and adding to it the indicated width of the bottom of the sill. Using this procedure, the width of the 1,072-fathom sill in Jungfern Passage was found to be 0·60 miles for the flat-bottomed section.

Assuming that the sounding track at this location was normal to the slope, an attempt was made to correct the apparent slopes of the walls of the "gap." The outline of the corrected shape of the feature is shown on Echogram Y, Fig. 2. This was the only place where the slopes were corrected. For other locations, the "apparent" slopes were measured from the bathymetric contours of Fig. 1.

The authors feel that the bathymetric data obtained from their surveys are not sufficient to warrant an attempt at any accurate calculation of the true slope of the irregular boundaries of the basin.

THE SILLS

The deepest link between the Atlantic Ocean and the Caribbean Sea appears to be through Anegada and Jungfern Passages (Table 1). As was demonstrated under "method," the controlling sill depth is 1,072 fathoms (true depth) at Jungfern Passage Sill.

* Since this sill lies beneath Jungfern Passage, it is called Jungfern Passage Sill. For the purposes of this report, the sill is confined to the feature extending from the 800-fathom curve, 16 miles southwest of St. Croix, westward along parallel 17°38′N to the 800-fathom curve of Grappler Bank. Likewise, the term Anegada Passage Sill is used for the sill under Anegada Passage.

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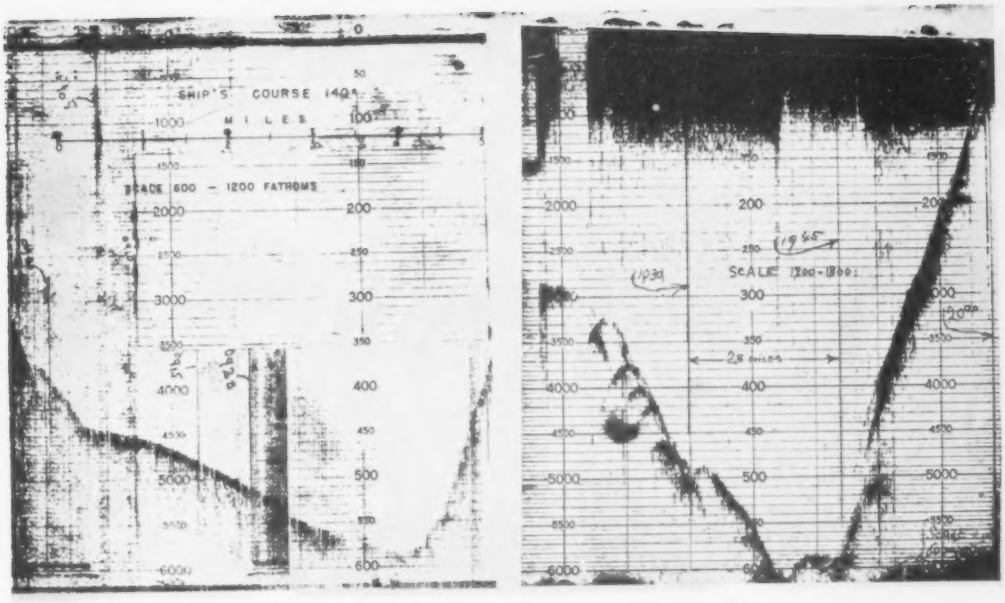

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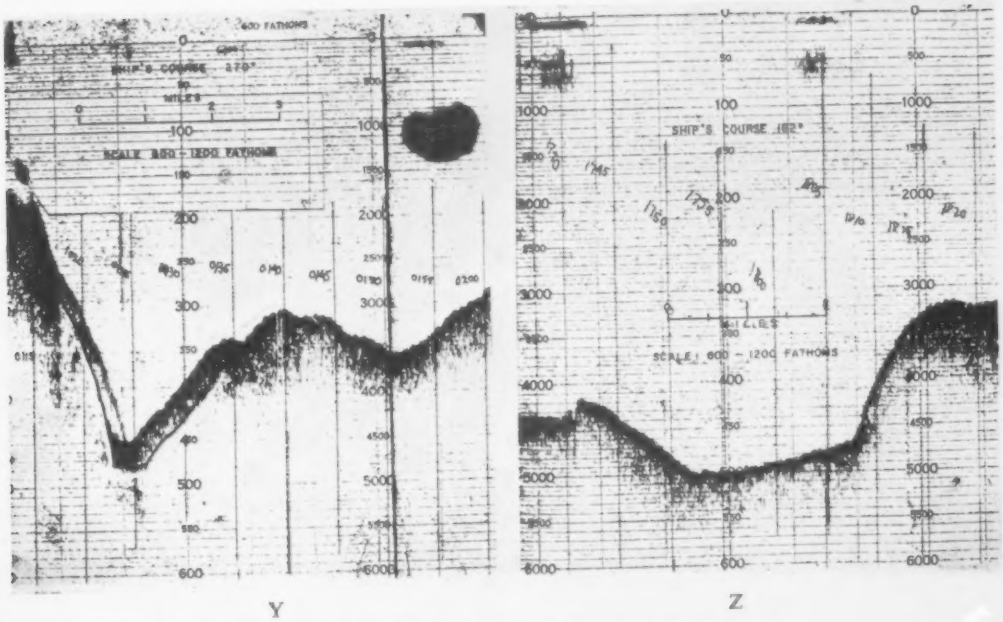

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Fig. 2. Bathograms as indicated on Fig. 3.

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From depths of 3,000 fathoms in the Atlantic Ocean east of Anegada, a canyon-shaped valley shoals continuously toward Anegada Passage between the Virgin Islands Platform and Barracuda Bank. Its head terminates south of St. John at Anegada Passage Sill (Fig 3). The recorded sill depth is 1,175 fathoms (true depth: 1,207 fathoms). This sill lies between the Virgin Islands Platform and a sea knoll 420 fathoms deep and separates the Atlantic Ocean from the Virgin Islands Basin. It is 9 miles wide at the 800-fathom isobath and 5 miles wide at the 1,000-fathom isobath.

Westward from this sill, another steep valley, which forms the northeast arm of the Virgin Islands Basin, slopes uniformly to the floor of the 2,400-fathom basin (SW-NE Profile, Fig. 4). On the southwest side of the Virgin Islands Basin, the bottom rises abruptly and irregularly towards Jungfern Passage Sill (Fig. 1).

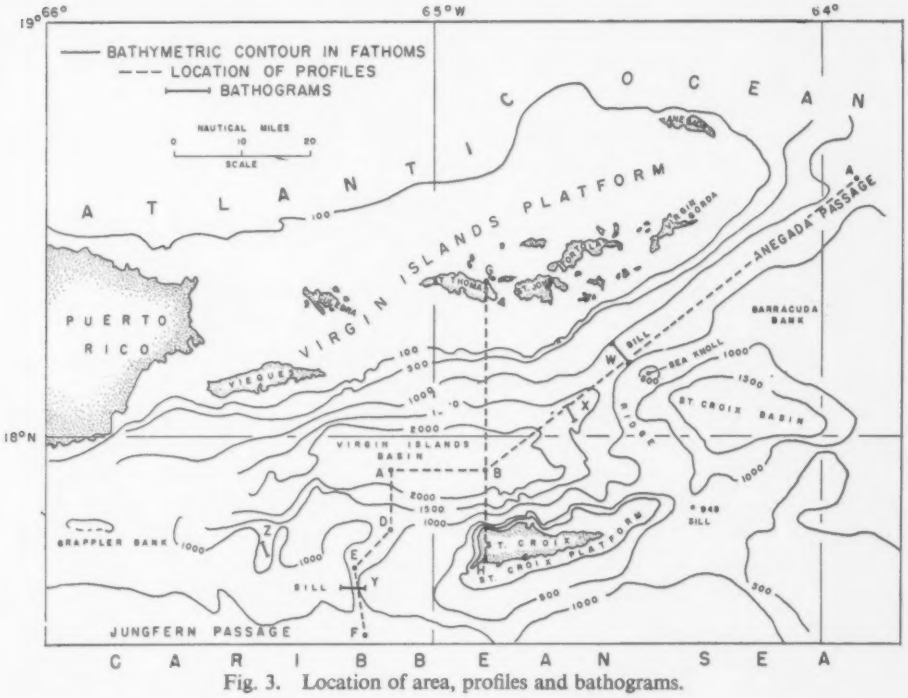

Fig. 3. Location of area, profiles and bathograms.

Jungfern Passage Sill was found to be 13 miles wide at the 800-fathom isobath and marked by two hills shoaling to 835 fathoms in its centre section and by one channel on its eastern end and one channel on its western end.

Its eastern channel (Echogram Y, Fig. 2) has a flat bottom 3/4 of a mile wide at a depth of 1,045 fathoms (true depth, 1,072 fathoms). It occurs at Long. 55°12′W, Lat. 17°35′N and represents the sill depth between Atlantic waters (which flow into the Virgin Islands Basin) and the Caribbean Sea. The shape of this section was corrected and traced as explained under " method." As a result, the walls of this gap were found to have a slope of 15° on the east and 5° on the west.

About 10 miles west of the above location, the western channel was found to be approximately 3 miles wide at the 900-fathom level. This section has not been com-

pletely surveyed, but careful study of the available fathograms indicates that its uncorrected depth should not be greater than 970 fathoms. The survey courses define the 900-fathom contour on the eastern and western sides and the 1,100-fathom contour on the northern side of the channel (Fathogram Z, Fig. 2). With the available data, it was possible to draw the 950-fathom contour line on the plotting sheet as shown in Fig 1. The bottom of the channel appears to be smooth and to shoal uniformly westward to Grappler Bank (Figs. 1 and 2).

The following table shows the charted sill depths of the passages separating the Atlantic Ocean from the Caribbean Sea. Jungfern Passage Sill appears to be the deepest of these.

Table 1

Windward Passage (15 miles wide at the 800-fathom isobath)	850 fathoms
Mona Passage	250 fathoms
Dominica Passage	750 fathoms
St. Lucia Channel	550 fathoms
Jungfern Passage (13 miles wide at the 800-fathom isobath)	1,072 fathoms

SUBMARINE TOPOGRAPHY

Two large basins, the Virgin Islands Basin and the St. Croix Basin, characterize the bottom topography of the area between St. Croix Island and the other Virgin Islands (Fig. 3). These two basins are separated by a winding ridge which has a northeasterly trend from the St. Croix Platform to Barracuda Bank to which it is probably connected at the 1,000-fathom level.

A sea knoll of elongated shape rises approximately 500 fathoms above the ridge and has a summit 420 fathoms deep (Fig 1). Six miles to the southwest, an elevation 565 fathoms deep was found separated from the summit by a saddle 640 fathoms deep. Numerous gully-shaped indentations were revealed on the flanks of the sea knoll.

The area east of Long. 60°20′W was not surveyed by the authors, but on a zero-degree course along this longitude the following interesting new facts were found:

1. The 1,400-fathom level in the Anegada Passage was crossed at this longitude and about Lat. 18°16′N (Fig. 1, northeastern side).*

2. The elongated sea knoll is 3½ miles wide at the 1,000-fathom level and only 3 miles west of the 1,000-fathom level of Barracuda Bank. Thus it may be assumed that the ridge is connected with the Barracuda Bank through a saddle probably 1,000 fathoms deep, south of Anegada Island.

3. The St. Croix Basin tends to flatten around the 1,600-fathom level. The deepest point of the basin is eastward. West of the ridge lies the Virgin Islands Basin, which was extensively surveyed by the authors. The basin has an east-west axis. It is 65 miles long and 17 to 20 miles wide at the 1,000-fathom isobath which includes its western appendix.

* This fact leads to the assumption that the elongated valley which merges into the Atlantic Ocean at Anegada Passage from the 1,175-fathom sill could slope continuously towards its deep end. The gradient at its head is about 2° and appears to be uniform.

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The proper Virgin Islands Basin may be confined by the 1,500-fathom contour, at which level it is about 45 miles long. To the north and south, this basin is bounded by escarpments (Profile N-S, Fig. 4) having an apparent slope ranging from 9 to 43 degrees, the steepest part being in the northwest and southwest side between the 1,500- and 2,000-fathom level. The floor of the Virgin Islands Basin was found to be flat, with depths ranging from 2,350 fathoms on the east to 2,400 fathoms on the west.

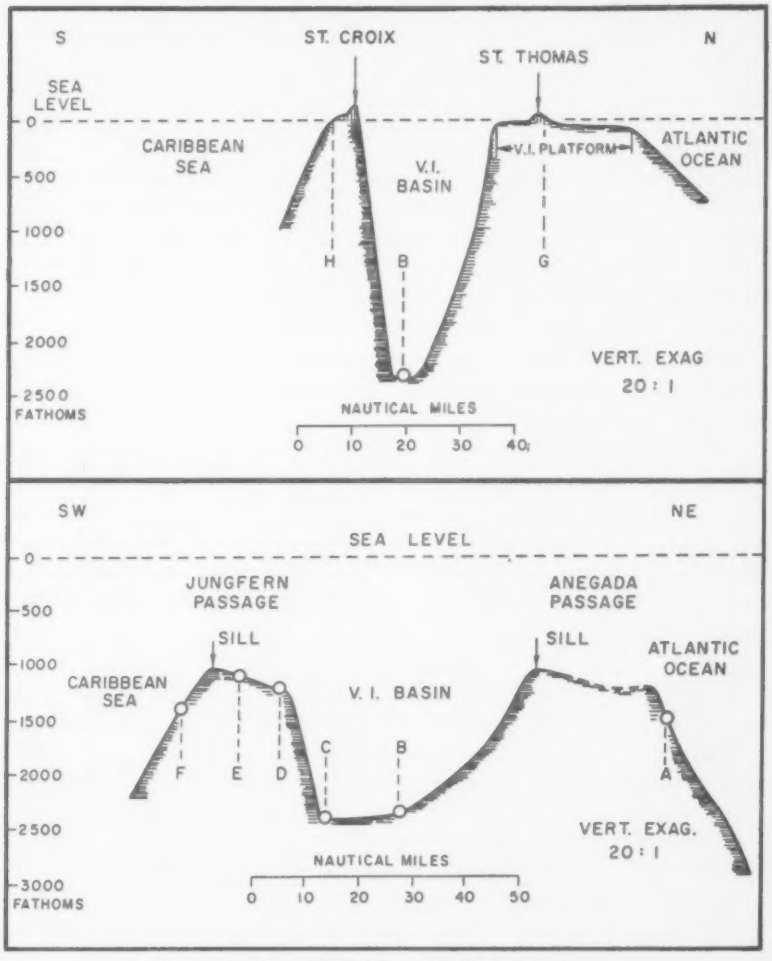

Fig. 4. Bathymetric Profiles as indicated on Fig. 3.

In relation to the indentations of the Virgin Islands Platform (Figs. 1 and 3) and the north coast of St. Croix, the margins of the Virgin Islands Basin are rather irregular, and the presence of numerous submarine furrows, which could not be surveyed in detail, was revealed in the few crossings near the margins of the basin.

The western side of the basin narrows, funnel like, into a 2,100-fathom gap about one mile wide with apparent slopes southward in the order of 40° and northward on the order of 30°. This gap leads into a secondary basin which has a flat floor

2,200 fathoms deep and approximately 10 miles long at the 1,500-fathom level. Westward, this secondary basin is bounded by Grappler Bank and southward by the Jungfern Passage Sill (Fig. 3).

The eastern side of the main basin is characterized by two canyon-like arms. The narrow floor of the northeastern arm (½ mile across at the point where it is most incised) (Echogram X, Fig. 2) has a 15-mile long curving axial trend with a 4° gradient from its delta between the 2,000- and 2,100-fathom levels to its head at the 1,175-fathom deep Anegada Passage Sill. Its northern wall, parallel to the rim of the Virgin Islands Platform, and its southern wall, on the sea knoll flank, are steep, having a relief of 300 to 800 fathoms. They are incised with small gully-like valleys which resemble canyon's tributaries and which may have been caused by landslides and mud flows on the side slopes.

It is possible that this feature may be of submarine fault origin (SCHUCHERT, 1935) and that consequent landslide and turbidity currents have modified the present feature of this arm (so that the canyon interpretation seems plausible). Unlike fault trenches, it has a V-shape and a winding course. Its floor slopes outward, continuously merging into the Virgin Islands Basin, and its walls have several tributaries mostly on the southern wall.

The southeastern arm slopes uniformly from its head on the ridge (about 900 fathoms deep) to the basin where it debouches in a sedimentary fan formation, north-northwest of Christianstead, St. Croix.

The fan is a flat, 2,100-fathom deep, 60° circle sector of 3 miles' radius embracing a sea high with a 100-fathom relief (Fig. 1). The fan terminates to the west where the lower sections of the basin deepen from 2,100 to 2,350 fathoms. The sea high may have acted as a dam which ponded sediments washed down the upper arm until it could spill over into the main basin. The soundings shown are amply supported by various other readings that were made at times when the ship was drifting.

DISCUSSION

The Virgin Islands Basin, because it is a fault block or an intermountain type basin, is somewhat of a tectonic anomaly in the otherwise typical island arc structure of the West Indies. It is the locus of several medium size earthquakes (GUTENBERG, 1937) and numerous minor shocks which, presumably, are associated with the seascarps that mark the northern and southern margins of the basin. The detailed topography presented in this report shows that the basin has a flat floor which probably consists of a thick layer of sediment (OFFICER, personal communication), which might be in part of Miocene age (MEYERHOFF, 1927).

North of Ham Bluff, St. Croix, a lump of white, inorganic sticky clay was retrieved with an anchor from the 2,350-fathom floor of the basin.* The fact that this floor is flat and deeper on its western end suggests that the original topography, after faulting, may have been buried by subsequent sedimentation deposited by turbidity currents flowing from the east.

Although several investigations have pointed out that turbidity currents are not known to erode (SHEPARD, 1954), it appears likely that on a steep slope a turbidity current can pick up unconsolidated sediment and transport it great distances (HEEZEN

* Due to a misunderstanding, the anchor was washed out before a sample of the interesting clay could be saved.

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and EWING, 1956). The following facts are offered as a basis for the hypothesis that the Virgin Islands Basin may be floored by sediments deposited by turbidity currents:

1. Earthquakes, which are known to start mud slides from slopes and thus cause turbidity currents, occur frequently in this area.

2. The walls of the basin are incised with canyon-like gullies and deep valleys, such as its northeastern and southeastern arms. These may be the channels that turbidity currents follows.

3. A sedimentary fan formation (MENARD, 1955) was found at the mouth of the southeastern arms of the basin which can best be explained in terms of turbidity currents. Moreover, clay was retrieved from the bottom of the deep basin but not from anchor hauls in the fan.

Acknowledgements—The authors take this opportunity to express their appreciation to the U. S. Navy for providing the facilities that made this operation possible and in particular they wish to thank Lt. Cdr. T. WATSON and Captain WALTER and his officers and men for painstaking and accurate navigation of their ships during the survey runs. They gratefully acknowledge the help received from their colleagues, Dr. R. A. FROSCH, Dr. LUDWIG H. GRABNER, Mr. GREGORY T. HOLUB, Mr. ORDWAY T. MANNING and Mrs. IRENE FIORE and Mrs. YVETTE DEFELICE for assistance in drafting and editing, respectively. Additional soundings were supplied by Lamont Geological Observatory through the courtesy of B. C. HEEZEN.

Columbia University Hudson Laboratories, Dobbs Ferry, N.Y. Contribution No. 13

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IN MEMORIAM

Vice-Admiral J. D. Nares
(1877-1957)

JOHN DODD NARES, younger son of Admiral Sir George Nares, K.C.B., F.R.S., of *Challenger* fame was born at Surbiton on the 11 December 1877 and died at Monaco on the 18 January 1957.

Nares entered the Navy as a Cadet at the age of 14 and on promotion to Sub-Lieutenant volunteered for the surveying branch thus following the example of his brother George. After a season in home waters, he was sent out to Australia and in the years 1899-1907 served in H.M. ships *Penguin* and *Dart* as assistant surveyor during which surveys of Queensland and New Zealand were undertaken. A short spell in England was followed by an appointment to the *Egeria* in British Columbia the last ten months of which saw him in command of the ship and in charge of his first survey.

The *Egeria* was paid off in 1911 and Nares took command of the *Fantome* in Australia and surveyed the Buccaneer Archipelago. From 1913-17 he served in the Hydrographic Department of the Admiralty the last two years as Superintendent of Charts. Joining the *Enterprise* in 1917, he saw active service in the Red Sea and on the coast of Palestine his valuable work in connection with operations against Gaza being recognised by the award of the D.S.O. Transferred to the *Merlin* he continued surveys in the Red Sea and Mediterranean until 1920 having been promoted to Captain the previous year. Thereafter his appointments alternated between the Admiralty; where he was first, Superintendent of Charts and later Assistant Hydrographer; and surveys overseas in H.M. ships *Endeavour* (West coast of Africa) and *Iroquois* (Straits of Malacca). His last service on the active list was as Assistant Hydrographer and on promotion to Rear Admiral in 1931 he was placed on the retired list.

In 1932 Nares was elected President of the Directing Committee of the International Hydrographic Bureau at Monaco and re-elected in 1937 and 1947 whilst from 1952 until his death he continued to be a director.

When France was occupied by the Germans, Nares returned to England and was re-employed in the Hydrographic Department being content to serve in the rank of Captain and once again carrying out the duties of Assistant Hydrographer.

The valuable work done by Admiral Nares both in the Navy and at Monaco fully illustrates his industry and thoroughness and to him and his fellow directors at the I.H.B. seamen and scientists interested in matters to do with the sea and many other walks of life owe a debt of gratitude for the material published by the Bureau, for their unfailing willingness to be of assistance and for the uniformity in the presentation of charts which they have fostered and in a large measure achieved.

Throughout his long life Nares was always ready to give a helping hand to all who sought his aid: he was by nature conciliatory and this trait must have been extremely helpful in a situation when discussions with other nationals were of daily occurrence. His friends were numerous and he was greatly respected and liked by all the varied people who live in or merely visit the Principality of Monaco.

In 1904, Nares married Adeline Chaffey, daughter of the Hon. Mr. Justice McIntyre of Tasmania, who with a daughter, survives him. His only son, Alastair was killed in action whilst serving in the Fleet Air Arm in North Africa.

In addition to the D.S.O., Nares was a Grand Officer of the Order of St. Charles, Monaco, he was A.D.C. to H.M. the King in 1930-31.

J. A. EDGELL

ANNOUNCEMENT

THE Geological Society of America announces publication of Memoir 67, the two-volume *Treatise on Marine Ecology and Paleoecology*. Volume 2, Paleoecology, edited by HARRY S. LADD, is scheduled for delivery in January or February, 1957.

More than 100 geologists, biologists, oceanographers, and other scientists have participated in the preparation of the *Treatise*, under the direction of a committee of the Division of Earth Sciences of the National Research Council.

The *Treatise* contains the results of some original research but is designed primarily as a summary and appraisal of work done in recent years in the fields of marine ecology and paleoecology. About one-third of each volume consists of annotated bibliographies of the principal organic groups. The bibliographies are not intended to be exhaustive but attempt to include the most recent and comprehensive references so that they should serve as good starting points for the literature on the ecology and paleoecology of a given group.

Volume 1, (JOEL W. HEDGPETH, editor) will appear later in 1957. It is an attempt to survey the voluminous literature of marine biology and oceanography and to summarize material of particular interest to geologists. It includes sections, each composed of several chapters, on the physical-chemical features of the environment, the biological features (including biogeography, symbiosis, etc.), the major communities and environments of marine, estuarine, and brackish water (including the Baltic, Black and Caspian seas), and various marine populations.

Volume 2 includes an introductory section on such matters as the preservation of fossils, the nature of paleoecological evidence, and the organic constituents of fossils. The main part of the volume includes a discussion of the origin of life and a series of chapters on the paleoecology of each of the geological periods as known from a particular area of North America, from Precambrian to Recent time, and a chapter on the future of paleoecology.

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A survey of ocean current theory

HENRY STOMMEL

(*Received* 25 *January* 1957)

INTRODUCTION

DURING the past half century there have been several independent lines of development of theory of ocean currents. The interconnections among them have not been generally recognized in the literature; but these are so interesting and instructive, especially from a physical point of view, that it seems worthwhile to attempt to describe and compare them in a brief survey article. Moreover it seemed desirable to try to isolate the basic physical ideas in each of the theoretical studies and to present them in pictorial diagrammatic form, without mathematics. The construction of the various models and of the illustrations is based, of course, on the full mathematical development.

HOUGH (1897) devoted a minor portion of his famous theoretical study of tides on a rotating globe to a discussion of the currents produced by a zonal distribution of precipitation and evaporation, ignoring friction. He found that a uniformly accelerated system of purely east-west geostrophic currents would exist, but because of the uncertainty of how to treat friction he was unable to obtain steady state solutions and thus to conclude whether precipitation and evaporation are capable of being a significant cause of real ocean currents. A more important limitation of HOUGH's ocean current model is the absence of meridional boundaries in the ocean. GOLDSBROUGH (1933) discussed a model with such boundaries and found that he could construct steady stationary current fields provided only that the integral of the precipitation-evaporation function, taken along each parallel of latitude between the two boundaries, vanishes. The steadiness of the GOLDSBROUGH solutions does not depend upon friction. However, Nature affords no guarantee that the above integral of the applied precipitation-evaporation distribution shall vanish, nor are the causes of oceanic circulation limited to precipitation and evaporation (HOUGH and GOLDSBROUGH did not imply they were so limited, but employed them for simplicity's sake).

Considered from the vantage point of the present, it is astonishing to recognize that the theories of HOUGH and GOLDSBROUGH, although as originally proposed, considered only evaporation-precipitation as a cause of currents, are actually more general than at first appears, and in fact contain the main dynamical features of our present view of oceanic circulation. Indeed, one needs merely to introduce two additional physical ideas:

(1) EKMAN's (1905) notion that the direct frictional stress of the wind is confined to a thin surface " boundary layer," and that viscous shearing stresses are unimportant dynamically in the deeper body of the ocean, excepting, perhaps, at the bottom.

(2) The concept of a narrow western boundary current of a highly frictional (MUNK and CARRIER, 1950; HIDAKA, 1950) and/or inertial (CHARNEY, 1955; MORGAN, 1956) character.

These physical ideas are applied to the HOUGH-GOLDSBROUGH models in the following way. EKMAN's frictional boundary layer provides a way of converting the field of applied wind stress into a field of vertical velocity just beneath the surface and just above the bottom. Hence the main body of ocean water can be treated as frictionless and in geostrophic motion. The analysis proceeds the same as for the model driven by precipitation-evaporation, the water being supplied or abstracted by convergent or divergent boundary layers at the top and bottom.

The second physical idea, that of the western boundary current, frees the forcing function from the above-mentioned unnatural integral constraint. Thus in GOLDSBROUGH's original model, if precipitation exceeded evaporation over a latitude circle between two meridional coasts, there would be a net transport toward the equator, and mass conservation would be violated in the steady state. It now appears physically that in fact a narrow return flow would develop along the western coast sufficient to preserve mass conservation. Today it is believed that the Gulf Stream itself is an example of such a higher-order-dynamics western boundary current. MUNK (1950), CHARNEY (1955), and MORGAN (1956) have discussed the conditions in such currents in some detail, but from the point of view of the general oceanic circulation the main interest is not in the detail, but the mere fact of their existence because they provide a means of satisfying mass conservation in oceans bounded by meridians for quite arbitrary forms of the forcing functions. From a physical point of view it seems that such meridional boundaries and their associated western boundary currents are perhaps the essential difference between the regimes of circulation in the ocean and the atmosphere.

The work of the tidal theorists was confined to homogeneous oceans. SVERDRUP (1947) showed that in the steady state vertical variations of density do not need to be taken into account explicitly providing vertically integrated velocities are employed rather than the velocities themselves. Moreover, MORGAN (1956) has shown that density stratification does not prevent the formation of western boundary currents. Thus the form of the vertically integrated velocity field in central oceanic regions (or, simply, the net transport field) is independent of the details of the density structure. This powerful simplification enables us to construct net transport fields of steady ocean current circulations caused by wind or by precipitation-evaporation quite easily. Within the same framework the thermohaline circulation appears as an internal mode, and completely vanishes when integrated vertically. There is one reservation about the method of vertical integration which should be stated explicitly: the method is strictly limited to cases where appreciable velocity does not extend to large-scale irregularities of the bottom. In the case of a homogeneous ocean this is patently not the case, but the tidal theorists have written their theories to accommodate non-uniformity of the depth. For example, LAMB (1932, p. 326) finds that non-uniformity of depth in models with uniform rotation introduces second class waves of much the same character as non-uniformity of rotation introduces on the betaplane, or spherical ocean of uniform depth. Also EKMAN (1932) recognized the analogous effects of non-uniform depth and non-uniform rotation in large-scale circulations. He called them topographic and planetary effects, but he did not construct a complete ocean current theory, evidently because of the want of the western boundary current.

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Another example of the close connection of the work of the tidal theorists with more recent studies in oceanography and meteorology is the topic of large-scale transient motions. Oceanographers and meteorologists distinguish between long inertio-gravitational waves on one hand, and quasi-geostrophic waves (e.g. planetary waves in the westerlies) on the other ; but this distinction is already implicit in the tidal theorists' classification of waves of the first and second class (LAMB, 1932, p. 350). The recent study of free and forced motions of a two-density layered ocean on the beta-plane by VERONIS and STOMMEL (1956) is really a study of these same waves of both external and internal modes. It is found that the transient response of the ocean to time-variable forces depends essentially upon the vertical density structure.

The current systems of HOUGH *and* GOLDSBROUGH

In order to compare more closely the solutions obtained by HOUGH and GOLDSBROUGH we take a particularly simple pattern of distribution of precipitation and evaporation: precipitation over one hemisphere, evaporation over the other. The two cases are distinguished by choosing these hemispheres as the northern and southern respectively in the HOUGH case, and as the western and eastern in the GOLDSBROUGH case. The only difference between the two cases is that the distribution of precipitation-evaporation has been rotated 90°. The motion in both cases is regarded as very slow so that inertial effects are negligible ; also friction is neglected. The rain does not impart momentum to the ocean; the ocean is homogeneous in density, uniform in undisturbed depth, and covers the entire globe.

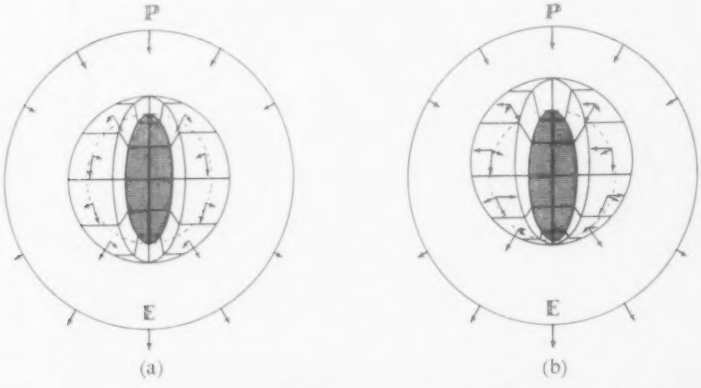

Fig. 1 (a and b). Two successive stages of the HOUGH-type circulation pattern, driven by precipitation distributed over the northern hemisphere (P) and evaporation distributed over the southern hemisphere. The hovering arrows indicate the distribution of precipitation-evaporation. The arrows drawn on the surface of the spheres are velocity components. The zonal currents grow with time. The central solid portion of the earth is shown as shaded in the cut-away mid-section.

First consider the HOUGH case, illustrated in Figs. 1 (a) and 1 (b), with precipitation in the northern hemisphere, and evaporation in the southern hemisphere. The solid lines are contours of equal precipitation-evaporation rate. The circulation is not steady, hence Figs. 1 (a) and 1 (b) represent two successive stages in the development of the field of flow. The elevation of the free surface and the zonal velocity component vary linearly with time as shown by comparing the two figures, but the meridional

component of velocity and the vertical component of velocity are independent of time. The horizontal components of velocity are independent of depth ; the vertical component of velocity varies linearly from the surface to żero at the bottom. At the surface the vertical component of velocity (measured positive from the centre of the globe) is the sum of the rate of increase of the elevation of the free surface and of the evaporation. Pressure is determined hydrostatically. As can been seen from the cut-away portions of Figs. 1 (a) and 1 (b), as time progresses not all of the water which is precipitated upon the northern hemisphere crosses the equator to the evaporation hemisphere, but some is used to build up an ever-increasing high-pressure region centred at the North Pole, and an ever-depressed low-pressure region grows around the South Pole. Thus meridional pressure gradients increase with time; and associated with them are two geostrophic zonal currents that also grow linearly with time. The zonal current is zero at the poles and at the equator. The meridional component of velocity is directed southward everywhere, and reaches its maximum where it crosses the equator. Although it flows from a region of high to a region of low pressure this meridional component is not driven by the pressure gradient, but is related through the Coriolis force only to the acceleration of the zonal current (remember there is no friction). Of course, a uniformly accelerated system of this kind persisting throughout all time is wholly unphysical – at some stage the velocities would no longer be small, our premise of slow motion would be violated, and at some stage the regime should become unstable or the effects of friction should intrude. Although instability of the flow pattern may be more plausible physically as a means of braking the motion, and indeed does seem to occur in the atmosphere, there is reason to believe, as we will see below, that in low latitude at least, the ocean circulation is stable. A simple braking of the currents in the HOUGH case can also be introduced by putting in a large virtual turbulent eddy viscosity, which leads to a steady state circulation pattern qualitatively similar to the pattern shown in Fig. 1 (b), as though the HOUGH solution were suddenly arrested. Introduction of large horizontal eddy viscosities is convenient mathematically, but the physical justification is doubtful.

The chief interest of the HOUGH case lies in the remarkable contrast which is produced by simply rotating the distribution of the precipitation-evaporation distribution 90°, so that the precipitation-evaporation maxima lie on the equator instead of at the poles. This is a special case of the GOLDSBROUGH type solution, shown in different views in Fig. 2. Here, even without friction, the field of pressure and flow is steady. Both horizontal velocity components are completely geostrophic – the flow is along isobars. The vertical component of velocity is zero at the bottom and varies linearly with depth up to the surface where it equals the precipitation-evaporation rate. The pressure field (obtained hydrostatically from the elevation of the free surface) is a rather complicated one. On the eastern edge of the hemisphere of precipitation there are two low-pressure cells; on the western edge, two high-pressure cells. The general pattern of flow is therefore a flow across both polar regions from the region of evaporation into the region of precipitation, and a flow in tropical and sub-tropical latitudes in the opposite direction. The difference of these two transports is, of course, equal to the precipitation in the western hemisphere.

The fact that there can be a net transfer of mass from one hemisphere to another by geostrophic flow in a closed system of isobars is simply a result of the fact that the

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Coriolis parameter varies along the meridian between the hemispheres. The lower the latitude the greater the transport between two isobars.

Geostrophic flow with a meridional component, in a homogeneous ocean of uniform depth, must exhibit a horizontal divergence – positive if directed toward the equator, negative if directed poleward. This is readily seen from Fig. 3 (a) in which a portion of a homogeneous, uniform depth ocean, bounded by two isobars

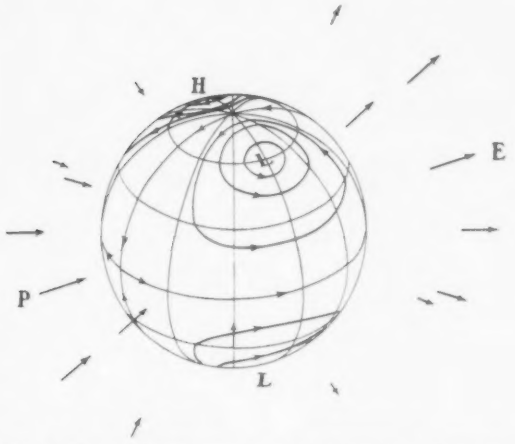

Fig. 2. The GOLDSBROUGH-type steady solution driven by precipitation over the western hemisphere, and evaporation over the eastern. The curve lines with arrows on them are isobars. The centers of high- and low-pressure cells are indicated by H and L.

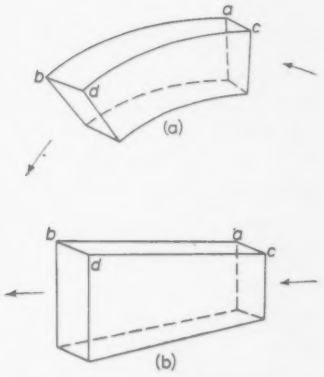

Fig. 3. (a) Divergence of geostrophic flow associated with change of latitude. (b) Divergence of geostrophic flow associated with non-uniform depth.

ab (high pressure) and *cd* (low pressure) is envisaged as flowing toward the equator. The pressure difference across section *ac* is thus the same as that across *bd*, independent of how wide these sections may be, but the Coriolis parameter is less at the latter, hence the geostrophic transport across *ac* is less than across *bd*. Inasmuch as no geostrophic flow can occur across *ab* and *cd* the excess of water must be supplied from somewhere – and in the steady system envisaged by GOLDSBROUGH this excess is provided by precipitation. In Fig. 2 the reader will note that the flow is entirely equatorward in the precipitation hemisphere. Similar remarks apply to poleward flows in the evaporation hemisphere. From a physical point of view the GOLDSBROUGH type circulation is constructed simply by choosing the particular system of geostrophic flow whose distribution of divergence (or convergence) is everywhere sufficient to absorb (or give up) the water locally precipitated (or evaporated). For certain types of precipitation-evaporation distribution there are no geostrophic flow patterns that can operate in this fashion, and it is under these circumstances that HOUGH-type solutions occur. Similar considerations apply to a plane ocean of variable depth (Fig. 3b), the geostrophic transport across *ac* being less than that across *bd* on account of lesser depth rather than larger Coriolis parameter.

Several further features of the GOLDSBROUGH solution should be mentioned here. First, in Fig. 2, it is clear that a coastal barrier could be placed along any complete isobar without affecting the solution, for example, along the meridional circle passing

through the centres of the precipitation and evaporation hemispheres, or as another example the equator itself could be replaced by a coastal barrier.

There is an important restriction upon the kinds of precipitation-evaporation distribution that allow of GOLDSBROUGH-type solutions. Since there can be no net steady geostrophic transport across a latitude circle it is necessary that the integral of the imposed distribution of precipitation or evaporation along a latitude circle shall vanish. This is a very severe restriction which no natural distribution of precipitation-evaporation necessarily fulfills.

Extension to the wind as a causal agent and to more general ocean-basin shapes

For the sake of simplicity we retain at this stage of the discussion the homogeneity of the ocean and its uniformity of depth, and inquire into more general causes of oceanic circulation and the influence of the introduction of various forms of coastal boundary.

EKMAN (1905) (or LAMB, 1932, p. 593) has shown that the currents directly produced by the stress of the wind are confined to a thin surface layer of less than 100 m thickness. Non-uniformity of the wind stress over the ocean causes a convergence or divergence within the EKMAN layer, and this integrated over the depth of the layer is independent of the details of the turbulent eddy structure of the layer. In the steady state, by conservation of mass, these distributions of net horizontal divergence produce an impressed vertical velocity on the top of the body of water immediately

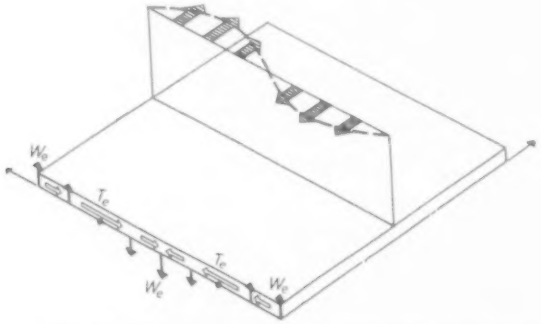

Fig. 4. The surface EKMAN layer, produced by a wind-field with sinusoidal pattern (the shaded arrows hovering above the surface). The EKMAN layer transports to the right of the wind are indicated by the open arrows labelled T_e. The vertical velocities produced by convergence and divergence of the EKMAN transports, and thus impressed upon lower layers, are indicated by solid arrows labelled w_e.

below the EKMAN layer. A particular example is illustrated in Fig. 4. The applied wind stress is purely zonal. The total transport of the wind-driven layer to the right (in the northern hemisphere) of the wind stress is indicated by the horizontal arrows labelled T_e. It is worth stating that the vertical scale in the diagrams is generally greatly exaggerated. Since these EKMAN transports are opposed, and since we can rule out an escape of water across the top surface, the water must escape the EKMAN layer from the bottom with a vertical component labelled w_e. Moreover, within the linearized dynamical framework under consideration, it does so without carrying any horizontal momentum with it. Thus it is immediately evident that so far as the deep frictionless layer is concerned it might just as well be operated upon by a precipi-

tation-evaporation distribution equivalent to w_e. We are thus permitted to investigate the transports of the deep layer within the framework of the HOUGH-GOLDSBROUGH-type solutions*.

The magnitude of w_e depends upon the magnitude of the curl of the quotient of the wind-stress and the Coriolis parameter. The mean pattern of wind-stress over the real oceans is predominantly a zonal one, and were the real ocean unbounded by coasts, would produce a HOUGH-type circulation, which, as we have seen, in the absence of friction or instability, does not admit a steady solution. However, if a meridional boundary is introduced it is possible to construct a steady solution starting at this boundary and working toward the west. SVERDRUP (1947) has shown that this is possible even in a density-layered ocean, but he does not explain why the development cannot be made eastward from a coast, nor does he indicate how the other side of the ocean is to be treated. Before attempting to explain these points, it is perhaps best to first describe a very simple SVERDRUP-type system: a homogeneous

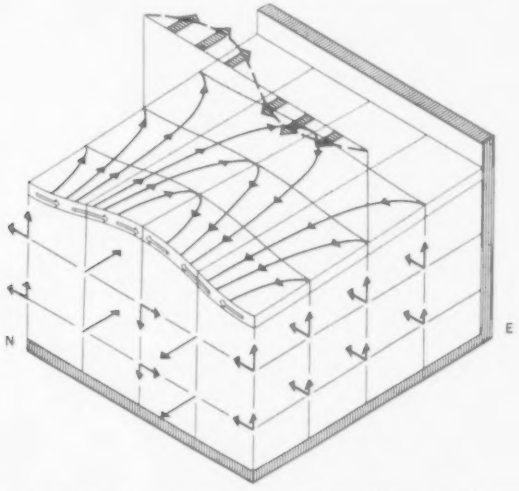

Fig. 5. SVERDRUP-type solution in homogeneous ocean of uniform depth, bounded by meridional coastal wall on the east. The wind system and EKMAN layer are the same as in Fig. 4. The curved lines with arrows on them are isobars ; the arrowheads indicate direction of the geostrophic horizontal flow (independent of depth). The components of velocity at a number of subsurface depths are shown by the solid arrows.

ocean, bounded by an eastern coast, and acted upon by a zonal wind stress. Fig. 5 shows the type of solution which applies in this case. At the surface there is a zonal wind stress similar to the distribution of the Northern Hemisphere westerlies and Trades over the real ocean. The mathematical solution from which the figure is drawn was obtained on the so-called beta-plane – a plane system of co-ordinates in which the Coriolis parameter is treated as a constant except where differentiated in the meridional direction. The transport of the EKMAN layer is indicated by the open arrows everywhere proportional to and to the right of, the wind. There is a vertically downward velocity imposed in central regions of the diagram: between the maximum

*Dr. K. YOSHIDA has pointed out to me that he and Dr. HAN-LEE MAO used these ideas in an unpublished (1954) paper on coastal upwelling off California.

westerlies and maximum easterlies. Outside this zonal belt the impressed vertical velocity is upward. From the bottom of the EKMAN layer to the bottom of the ocean this vertical velocity component diminishes linearly to zero. This water is absorbed, so to speak, by the divergence of the meridional component of the geostrophic velocity. Thus at midlatitudes where the vertical velocity is downward, the meridional component of geostrophic velocity is southward. The zonal components of the geostrophic transport are introduced to preserve mass continuity. At the latitude of maximum westerlies, for example, where there is no impressed vertical velocity the geostrophic flow is entirely zonal, diminishing linearly toward the coast. The contours of surface height, which determine the pressure field associated with the geostrophic flow field, are also shown in Fig. 5. The reader will remember that we are here dealing with a specially simplified case of the SVERDRUP-type model. We have constructed a geostrophic current system, consistent with the eastern coastal boundary condition which matches by its field of divergence and convergence (due to the meridional variation of the Coriolis parameter) the impressed field of convergence and divergence of the thin surface EKMAN wind-driven layer. We have obtained a steady-state solution. But it is also evident that we cannot satisfy conditions at the

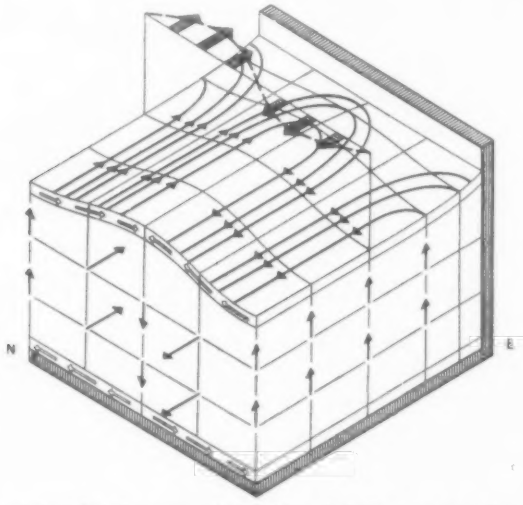

Fig. 6. EKMAN-type solution for the same wind field and shape ocean as shown in Fig. 5. In this case, with no divergence associated with geostrophic meridional currents, the compensating divergence occurs in a bottom frictional layer.

western coast unless some additional physical feature is introduced. But before looking further into this question, let us first consider what is involved if the eastern coast is removed. The there will be no possibility of an east-west pressure gradient, no meridional component of geostrophic flow, and the solution would accelerate. EKMAN has already discussed this case. He suggests that one may introduce a bottom frictional layer, with transports just opposite to those in the surface wind-driven layer. The final current system consists of three layers: the surface EKMAN layer, the intermediate layer of geostrophic flow, and a bottom EKMAN layer. The vertical velocity is constant with depth within the geostrophic layer (which being purely

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zonal has no horizontal divergence). The amplitude of the geostrophic current at mid-depths depends entirely upon the size of the frictional coefficients of the bottom layer. If there were no variation of the Coriolis parameter with latitude a meridional wall would cause the zonal current to turn around within a region more or less as wide as the width of the zonal current (Fig. 6), and the amplitudes of the motion would not be affected markedly. Far from the coast the flow is the same as in the absence of the coastal barrier. In Fig. 5, which has both the wall and variation of Coriolis parameter with latitude the situation is quite different: the flow never becomes purely zonal no matter how far removed from the coast one may be. A number of further comparisons between the regimes indicated in Fig. 5 and 6 can be seen by studying the illustrations: note for example the different dependence of the vertical velocity component upon depth in the two cases, the different form the surface elevation, etc. There are also marked quantitative differences in the transports in the two models: for example if the depth is increased in Fig. 5 the geostrophic transport remains constant, but the velocity decreases, but in Fig. 6 the geostrophic transport increases and the geostrophic velocity remains constant.

Further complications of the simple homogeneous model are, of course, possible. Non-uniform rotation and bottom friction may be both introduced simultaneously, also lateral friction, and even bottom topography of various simple forms. MUNK (1950) has given an indication of the possible role of lateral friction near the eastern coast. Quantitative comparison of the transports in simple models and as inferred from hydrographic data suggests that in the middle regions of sub-tropical and equatorial oceans, at least, topographic and frictional influences play a negligible role, and that the dynamical framework shown in Fig. 5 is more akin to that of the real ocean than that of Fig. 6. Lack of friction places an upper limit on the realizable transport in ocean currents, and this seems to be realized (e.g. SVERDRUP, 1947 ; REID, 1948, etc).

The fact that higher order physical processes might be important only at the western boundary of the oceans was first suggested by MUNK's (1950) grouping of the terms in his solution for a wind-driven, laterally viscous ocean. CARRIER (MUNK and CARRIER 1950) was apparently the first to recognize that this was tantamount to treating the intense western current by the mathematical technique of the boundary layer; that is to say, for certain values of the physical parameters determining ocean circulation the higher order effects of friction and inertia can be neglected everywhere in the ocean except in the theory of the narrow high velocity current along the western coast of the ocean. For further details about the theories and observational material on the viscous western boundary current, and the more recent inertial theory, I refer the reader to my book on the Gulf Stream (STOMMEL, 1957).

The main point that ought to be made here is that we can always fit a narrow western boundary current to a SVERDRUP- or GOLDSBROUGH-type solution. And we can do it symbolically – there is little to gain, from the point of view of the large-scale mid-ocean general circulation, by attempting to discuss the detailed structure of the western boundary current. We regard the western boundary current as a device for satisfying mass conservation and applying a physically realistic western boundary condition. In a word, it frees us from the crippling restriction upon the distribution of the driving agency already indicated by GOLDSBROUGH (above).

It would be misleading to give the impression that the theory of the western

boundary current is complete. There is a complete theory of the purely lateral-viscous western boundary current (MUNK 1950; MUNK and CARRIER, 1950), but the theory, so far developed, of the inertial boundary current applies only to the growth region, or region of formation of the western current – where the transport of the stream increases in the down stream direction. The remainder of the inertial boundary current, where it must gradually leave the boundary and broaden out to join the sluggish interior solution, has not been studied. Evidently in nature, there is a rather complicated "decay region," meanders and breakdown of the western current, and a tendency of the boundary current to pull away from the coast bodily and thus to penetrate quite far into the interior without at once diminishing its narrow intense character (FOFONOFF's (1954) free solutions are enlightening in this respect).

The chief ingredients of the ocean current as outlined here are as follows :

(1) The simple precipitation-evaporation distribution may be replaced by an EKMAN-type wind-driven surface layer.

(2) A meridional boundary converts an otherwise accelerated Hough-type solution to a steady GOLDSBROUGH-type one, developed westward from the boundary.

(3) A western boundary current preserves mass conservation and satisfies the boundary conditions at the western boundary of the ocean.

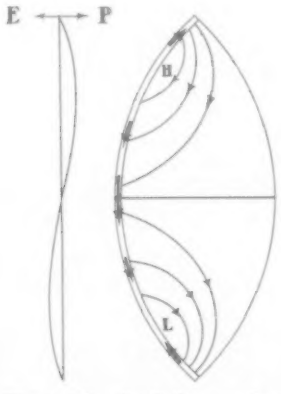

Fig. 7. The steady circulation produced in a uniform depth ocean bounded by meridional coasts 60° apart under the influence of precipitation in the northern hemisphere and evaporation of the southern hemisphere. The curve lines with arrowheads are isobars. The western boundary current is drawn schematically within the double line on the western coast.

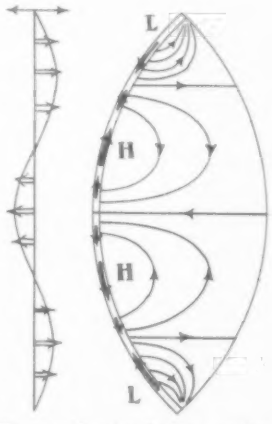

Fig. 8. The steady circulation produced in an ocean of same shape as that in Fig. 7, but acted upon by a particular distribution of zonal winds, shown at the left. The western boundary current is shown schematically by the double line at the western coast, and its transport is indicated by heavy arrows.

Further, as SVERDRUP (1947) has shown in the steady-state vertical density stratification does not materially affect the conclusion. SVERDRUP's well-known curl-equation merely states that the meridional component of the vertically integrated geostrophic transport at each point in the ocean is precisely that required to counterbalance the divergence impressed by the Ekman laver. The zonal component of the vertically

integrated transport is obtained from the continuity equation, and the boundary condition of no normal transport through the eastern coast. The discussion of internal modes of circulation, whose vertically integrated transport vanishes, is reserved until later.

In order to demonstrate these ideas implemented in two special cases, Figs. 7 and 8 have been prepared. In each case the ocean is bounded by meridians 60° apart. In Fig. 7 the northern hemisphere is one of precipitation, the southern of evaporation. The distribution of precipitation-evaporation is somewhat similar to that shown in Fig. 1, except near the poles where it has been altered to avoid infinities, but otherwise it would be expected, in the absence of the meridional barriers, to lead to an accelerated HOUGH-type system. The presence of the meridional barriers permits pressure gradients along the latitude circles, and a steady geostrophic flow field with meridional components. The impressed precipitation or evaporation is absorbed or given up by the meridional geostrophic flow at each point in the ocean. The isobars, or lines of equal elevation of the sea-surface are shown. The flow is along these lines, but they are not transport lines, of course. The eastern coast and equator are isobaric. At the equator, where there is no evaporation or precipitation in Fig. 7, there is no meridional component of geostrophic flow; hence all of the water precipitated in the northern hemisphere must cross the equator at the western coast as a western boundary current. Slightly north and south of the equator there are meridional components of flow in the central portions of the ocean, but these are not sufficient to carry all the flow across the latitude circle that is required by mass conservation, so that much of this flow likewise occurs in the western boundary current. At sufficiently high latitudes the meridional geostrophic transport is just sufficient to carry away the mass added further northward: there is no western boundary current at these latitudes. Poleward of these points the mid-ocean geostrophic transports exceed the available supply of water added by precipitation to the northward, and hence the western boundary currents reverse, and actually flow toward the north.

In Fig. 8 a similar model is portrayed, except that here the causal agent is a zonal wind-stress distribution (indicated to the left) blowing upon an ocean, also with meridional boundaries 60° a part. Between 30° latitude and the poles prevailing westerlies are depicted; the trades extend across the equator from 30°S to 30°N latitude. This is, of course, only a very crude representation of the real wind system over the globe. The lines are isobars parallelling the geostrophic flow. In this case there is a certain amount of EKMAN wind-drift transport in the surface layers which ought to be added to the geostrophic transport field to give an accurate picture of the total transport field, but this is omitted in the figure to preserve simplicity of presentation. Here we obtain, by a series of arguments similar to those used in justifying Fig. 7, a system of gyres and western currents resembling that obtained in the complete theory of MUNK (1950) and HIDAKA (1950). The boundaries between the gyres correspond to latitudes of no EKMAN layer convergence. The regions of maximum geostrophic meridional flows in each gyre correspond to the latitudes of maximum convergence (equatorward flow) or divergence (poleward meridional flow) of the EKMAN wind-driven layer. The zonal geostrophic transports are constructed by continuity from the eastern coast, and western boundary currents are fitted where needed to conserve mass.

Some of the features of the oceanic circulations described in this section have been

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qualitatively reproduced by VON ARX (1954) in a circular rotating basin using a density-homogeneous water layer of non-uniform depth. VON ARX's model is driven by applied wind-stress. In experimental work it is not possible to avoid bottom friction altogether, but evidently, with sufficiently deep layers the divergence of meridional geostrophic flows dominates over that of the bottom frictional layer. To date, quantitative experimental studies have not been made.

Some integral relations pertaining to thermohaline and internal mode circulations and application to interpretation of the atlantic ocean circulation

Before proceeding to the topic of the next section, where an effort is made to visualize the physical factors governing the vertical density distribution in the ocean, it is perhaps worthwhile to indicate here that formally, the simple ideas described above, and applied to a homogeneous or vertically integrated ocean, can also be employed to elucidate certain features of internal modes of circulation in the ocean by simply dividing the ocean into two layers by a *level surface* at mid-depth, say 1500 or 2000 m and specifying the vertical mass transport across this level surface as a function of geographical position. What is taken from one layer is added to the other. A pattern of geostrophic flow can be constructed in each layer to absorb

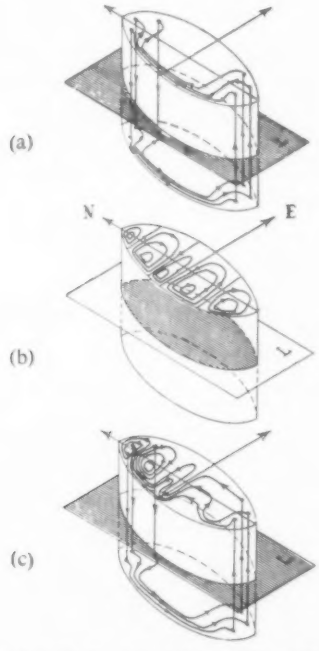

Fig. 9. A schematic interpretation of the circulation in the Atlantic Ocean constructed by superposition of an internal mode associated with flow across a level surface *L* at mid-depth (a) and a purely wind-driven circulation in the surface layers (b). The sub of these two is shown in figure (c).

(or give up) the water required for the vertical transport across the level surface, and a western boundary current fitted where needed in each layer. The vertically integrated transport over both layers taken together vanishes: the circulation is a

pure internal mode, except perhaps where topographic effects dominate. These considerations, and the pictures derivable from them, are not *theories*. They merely provide an interpretative tool, and indicate what flow patterns must be associated with various distributions of vertical transport across level surfaces. As an illustration of the use of this tool, a rudimentary interpretation of the Atlantic Ocean circulation is presented here.

Consider the schematic ocean drawn in Fig. 9 (a), extending from pole to pole across the equator and bounded by meridional boundaries roughly 60° apart. A level surface L which divides the ocean into an upper and a lower layer is also shown. Now suppose that some thermohaline process, into the nature of which we do not here inquire, causes a sinking of water across the level surface in subarctic latitudes, and a rising of water across the level surface in subantarctic latitudes, as indicated by the vertical transport lines drawn in Fig. 9 (a) across the level surface. Our argument is that having specified the quantity and location of the vertical transport across level L, the rest of the transport picture in each layer is completely determined, in fact looks very much like that shown in Fig. 7 for a different physical situation.

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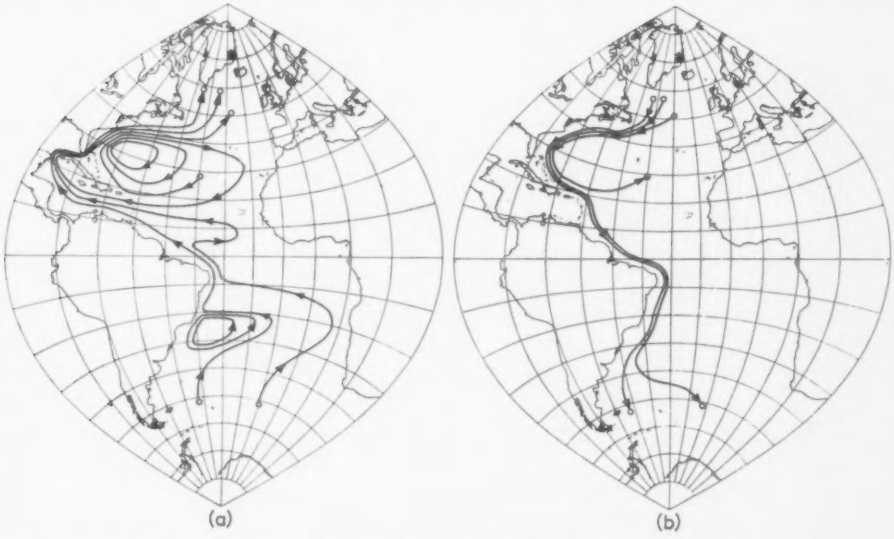

Fig. 10. A similar interpretation of the total transports in the surface layer (a) and bottom layer (b) but drawn on a chart of the Atlantic Ocean. Points of sinking and upwelling across the level surface are indicated by the little circles.

Thus for example, in the subarctic regions of the mid-oceanic portions of the upper layer the horizontal flow field is convergent, hence it must have a northward directed meridional component. The zonal component is determined by continuity, starting at the eastern boundary. Similar reasoning is applied to the lower layer and then to both layers in the subantarctic region. In subtropical and tropical latitudes we have specified no vertical transport across the level surface, and there is no geostrophic in the mid-oceanic regions of either layer. The transport of water between hemispheres which is required for conservation of upper layer and lower layer water separately must be accomplished by a narrow western boundary current. The field of motion

is entirely internal; its vertically integrated transport vanishes everywhere. Fig. 10 (a) portrays the resulting circulation pattern.

Now consider separately a wind-driven circulation in the upper layer maintained by the impressed vertical velocity field due to an EKMAN layer as shown in Fig. 9 (b). It looks much like that shown in Fig. 8, except that there is an additional gyre just north of the equator (after MUNK, 1950) which is presumably caused by the existence of a doldrum area in the winds just north of the equator. Within the simple framework of the linear mechanics of the models under consideration these two circulations (Figs. 10 a and 10 b) are additive. The sum is shown in Fig. 9 c. Note the absence of the Brazil Current, the very intense Gulf Stream. The picture looks much more realistic than the simple gyre system (Fig. 9 b) alone. A slightly different interpretation is drawn in Fig. 10 upon two charts of the Atlantic Ocean, the right figure representing the lower layer, the left the upper layer, and I have placed the diving reference level at 1500 metres. It seems probable that over subtropical and tropical latitudes there must be certain small upward flux of mass across the level surface to maintain the observed vertical increase of density with depth against eddy diffusion, so I have drawn the figure showing one transport line ascending through the reference level in midlatitudes. Each transport line corresponds to about 10 million m^3/sec. There are a number of features in this diagram which should be noted. For example, the vertically integrated transports of the Brazil Current and the Gulf Stream are the same, but according to the interpretation suggested here the current in the deep layer opposes the Gulf Stream, whereas it has the same direction as the Brazil Current. The opposite is true in the upper layer: the Gulf Stream is re-enforced by the thermohaline component, the Brazil Current so weakened that it almost disappears. The number of solenoids (intersections of surfaces of equal pressure and specific volume) in the Gulf Stream is very much greater than in the Brazil Current, thus by ordinary oceanographic reasoning the Gulf Stream would look like a current of very much greater transport than the Brazil Current. We identify the deep current with North Atlantic Deep Water. The reader will find it interesting to examine in some detail such features as the vanishing of the western current in the region of latitude of the Equatorial Counter-current, the curious spiral in the subarctic region of Fig. 9 (c), etc. This picture of the circulation of the Atlantic is certainly not to be dignified by calling it a theory. It is simply offered as an interesting example of how far reaching the consequences of specifying the vertical velocity at the surface and some mid-depth level can be.

There is a further reason for focussing attention on the vital role played by the vertical velocity distribution, and hence the field of horizontal divergence in the ocean: namely, to emphasize the danger of making the assumption that because the vertical velocity is small it may be neglected – or even arbitrarily set equal to zero. For example, HIDAKA (1955) has recently worked out an elaborate numerical theory of the general circulation of the Pacific Ocean, interpreting it as a purely wind-driven phenomenon and assuming that the vertical velocity vanishes exactly everywhere. As HIDAKA himself has commented there is no clear physical explanation or interpretation of his numerical results ; indeed, from the point of view of this survey, it could hardly be otherwise. As I see it, the chief way that the Ekman layer affects deeper portions of the ocean is by imposing a vertical velocity upon them at

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the top, and chief agent of the thermohaline circulation is the slow vertical advection of density which balances the vertical diffusive loss of density to the surface.

Another example is NEUMANN's attempt (1955) to identify DEFANT's intuitive choice of reference level (DEFANT, 1941) in the Atlantic Ocean with a rigid impenetrable surface through which no water can pass. As I have indicated elsewhere (STOMMEL, 1956) the DEFANT level may actually be the level of no horizontal divergence in the ocean, in other words the level of maximum vertical velocity. This review is no place to attempt a detailed critique of the above studies of HIDAKA and NEUMANN. One can only point out that, on physical grounds, the field of vertical velocity is so intimately connected with the large scale circulation patterns that arbitrary assumptions about the vertical velocity structure in the ocean are attended by the most far-reaching implications concerning the form of the horizontal current patterns; and that unless this is fully recognized in setting up theoretical models, the results may be disastrous.

Extension to density-layered models in the steady state

The fact that SVERDRUP's theory gives the field of vertically integrated transport makes it possible to construct certain elementary models in which the density layering

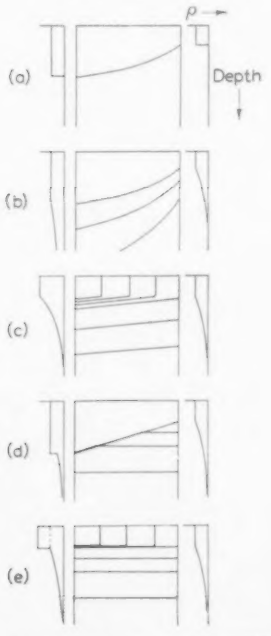

Fig. 11. These five vertical profiles (a, b, c, d, e) show the density structure which different models obtain in the plane *AA'B* of Fig. 12. See text for explanation.

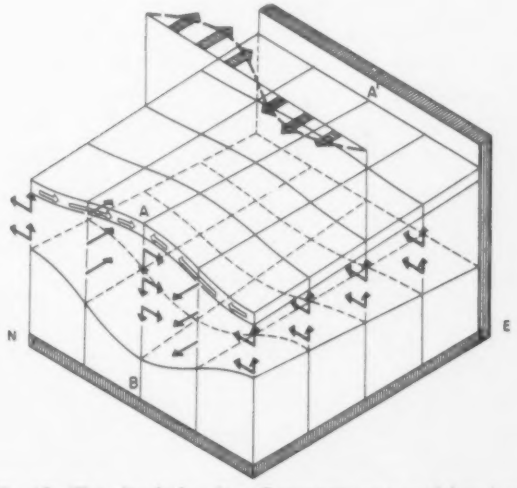

Fig. 12. The circulation in a SVERDRUP-type model such as shown in Fig. 5, but with two immiscible layers of slightly different density. The interface is shown by dashed lines.

is specifically taken into account. The most elementary model is one in which the density is essentially inactive – that is to say, the amount of water of each density is specified to begin with; no particle of water can change its density. One thus con-

siders density as an immiscible property – various portions of the ocean remain unmixed, like layers of oil and water. This is, of course, a considerable oversimplification of the state of affairs in nature.

For example one might consider an ocean consisting of two separate layers each of uniform density, the top layer being slightly less dense than the lower layer. A vertical sounding (of density against depth) in such an ocean would look like one of the curves in Fig. 11 (a). If there is no friction across the interface, and the ocean bottom is of uniform depth, the deep layer cannot move, and the slope of the interface must entirely counterbalance the horizontal pressure gradient associated with the geostrophic flow in the upper layer. If the distribution of wind is the same as that shown in the homogeneous model depicted in Fig. 5, the state of the two-layer system is as depicted in Fig. 12. The vertical section of the density field along the latitude of maximum wind-stress curl (the $AA'B$ plane) is shown in Fig. 11 (a). The densities of the two layers are taken as constants in the model. The depth of the interface at the eastern coast is also an arbitrary constant. The functional dependence of the depth of the interface on position, subject to the constraint of the SVERDRUP theory, is then completely determined. Since there must be the same geostrophic transport to the south across each unit width of the section, and the depth of the interface increases by a marked fraction of its mean value, the geostrophic velocities and slope of the interface must diminish somewhat with distance from the wall.

REID (1948) has given another model which exhibits much similarity with reality, based upon an arbitrary vertical distribution of density sketched in Fig. 11 (b). Here the ocean is covered everywhere by a thin homogeneous layer of uniform density, but of variable depth, and is underlain by a region in which the density increases to a fixed bottom density by an exponential law – the coefficient of depth in the exponential function being inversely proportional to the depth of the homogeneous upper layer. This is, of course, a very special form of density law, but it must be said that it closely resembles the form of density distribution in the Eastern Equatorial Pacific quite well. As in two-layer model it contains only one dependent variable. Again the functional form of this variable is completely specified subject to SVERDRUP's constraint on the distribution of vertically integrated transport. The analog of the vertical density profile along the latitude of maximum curl of the wind stress for REID's density model is shown in Fig. 11 (b).

STOCKMANN (1953) has worked with a different type of density field. Suppose that a density anomaly is defined by subtracting from actual densities the bottom density, and at the eastern wall a density anomaly vs depth curve is drawn of any arbitrary or observed shape (Fig. 11 c). The density structure at other stations is now assumed to be formed by multiplying the given curve by a constant factor (constant with depth at any one station, but variable from station to station). This again is an attempt to describe the density field in terms of a single dependent variable. The density field along $AA'B$ according to STOCKMANN's model is sketched in Fig. 11 (c).

It is important to note, at this point, that in the models of REID and STOCKMANN, the fluid cannot be regarded as inactive or immiscible. There is in both models an unstated but implicit assumption about transfer of mass across isopycnic surfaces. The deeper layers are supposed, in the section $AA'B$ to be moving geostrophically in a meridional direction, and this can only occur with divergence. In the top layer this horizontal divergence is balanced by the impressed vertical velocity from the

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EKMAN surface layer ; in deeper layers by a flow across isopycnic surfaces. Thus strictly speaking an explicit assumption of immiscibility would lead to profiles of the form shown in Figs. 11 (d) and 11 (e), instead of those of 11 (b) and 11 (c). Indeed it ought to be possible to compute the amount of mixing in nature from these considerations (STOMMEL, 1956).

The models mentioned above suffer being highly artificial, highly specified in form of the density field, and even more disconcerting, they involve implicit assumptions about the nature of the mixing processes. It would be very interesting to invert the problem: to make explicit assumptions about the nature of the mixing processes and, subject to integral constraints of the SVERDRUP kind, to find the resulting density fields. One might even hope to find a partial explanation of the main thermocline.

The pioneer effort in this direction is reported in an important Russian paper by LINEYKIN (1955). The model, and its implications, are best described in terms of the

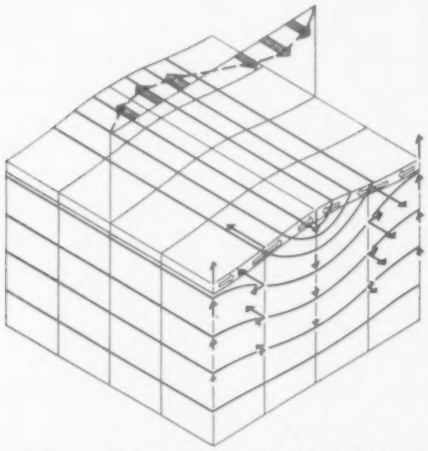

Fig. 13. LINEYKIN's explanation of the depth to which the baroclinic geostrophic currents produced by the wind extend in a stable ocean. The isopycnal surfaces are shown by the wavy nearly horizontal solid lines. The velocity components are shown by solid arrows.

illustration in Fig. 13. One begins by considering a basic state in which there is no motion – and no wind blowing over the ocean. There is, however, a uniform vertical stability maintained by vertical eddy conduction. We might suppose for example that the ocean is heated from above, and cooled from below, thus maintaining a constant and uniform heat flux downward, and a stable stratification of density. This is, it must be admitted, a rather artificial way to begin – the only excuse for it is that this conductive stable state is used as a basic state upon which to build a linearized perturbation theory when the surface is subjected to an infinitesimal wind-stress distribution of the form indicated by the large arrows hovering over the diagram. In the surface there is an EKMAN transport to the right of the wind, and an impressed vertical velocity field just beneath it. LINEYKIN found that if the Coriolis parameter is taken as a constant, and for such choice of the parameters as make the scale of the phenomenon truly oceanic, this vertical velocity perturbs the density field by vertical advection of heavy in such a way as to produce a perturbed field as portrayed by the lines in Fig. 13. Isopycnals are depressed in regions of downward flow, and vice versa.

Where the isopycnals slope most strongly the geostrophic subsurface currents are strongest. As is shown by the velocity arrows, this subsurface geostrophic current is generally in the direction of the surface wind, and there is a small non-geostrophic component (below the EKMAN layer but associated with friction) across the isopycnals directed from the region of downwelling toward the region of upwelling. This non-geostrophic flow at mid-depth compensates for the divergence of the EKMAN surface layer.

The most interesting feature of LINEYKIN's model is the fact that the geostrophic currents decrease exponentially with depth at a rate completely determined by the physical parameters of the problem (and not by arbitrary assumption). LINEYKIN has treated the problem rather generally, retaining non-isotropic viscosity and diffusivity, etc. But for the purposes of this exposition we ignore large-scale lateral turbulent exchanges, and hence, on account of the small vertical scale of the phenomenon (remember the vertical scale in the diagrams is greatly exaggerated) only vertical viscous and diffusive transports need be considered. It may be shown that if the turbulent coefficients of viscosity and diffusivity are roughly of the same magnitude – which there is generally reason to suppose is the case and, as in fact LINEYKIN does – the depth to which the geostrophic currents extend is independent of the eddy coefficients. This LINEYKIN-depth depends only upon the geometry of the system, the unperturbed vertical stability, and the Coriolis parameter. If the LINEYKIN-depth be defined as that depth at which the amplitude of the density perturbation is reduced to $\exp(-\pi)$ of its service amplitude, the ratio of the LINEYKIN-depth to the half-wavelength of the wind system is equal to the ratio of the Coriolis frequency f to the VAISALA or BRUNT frequency, $\sqrt{gs}$, where s is the mean stability of the model. In midlatitudes this ratio must be taken somewhere between 0·1 and 0·01, but in the neighbourhood of the equator it is certainly much less. One can see, therefore that although the LINEYKIN depth may be a fair representation of, and model for, the depth of the baroclinic layer in a small basin such as the Caspian Sea, it is several orders of magnitude too great to provide a reasonable explanation of the depth of the main thermocline in the oceans in midlatitudes. This, of course, does not detract the fact that LINEYKIN's paper has been a most stimulating and interesting one.

It seems likely that it is necessary to construct a somewhat different version of the LINEYKIN model to account for the density field in the ocean. In particular one would like to introduce the variation of the Coriolis parameter with latitude, since this has already been demonstrated to produce a marked tendency toward limiting currents to the upper layers (VERONIS and STOMMEL, 1956).

VERONIS and I have shown (VERONIS and STOMMEL, 1957) in a short contribution to the theory of thermally driven circulations based upon the LINEYKIN stable model, how the introduction of the variable Coriolis parameter modifies the depth obtained in uniform rotation (the LINEYKIN depth). I will give here a slight modification of these published results to make the physics as clear as possible. Consider (Fig. 14) a horizontal layer of fluid conducting heat downward by eddy conduction from a fixed hot surface temperature, to a fixed cold bottom temperature. Now suppose we can add water to the top, or take it away, without altering the fixed surface temperature. We can effect this, for example, by imposing a distribution of bands of precipitation and evaporation parallel to meridians (indicated in Fig. 14 by the hovering arrows), or probably equally well by putting a thin wind-driven EKMAN

layer on top. Thus in Fig. 14 the vertical velocity imposed at the top surface is a function of longitude only, downward in the mid portions of the diagram, and upward along the outer east and west edges. At some distance below the surface the temperature field is perturbed by the vertical advection of heat, which in turn is held steady by conductive reaction of the perturbed temperature field. The model shown in Fig. 14 is computed in a beta-plane, so that vertical gradients of the vertical velocity are intimately related to the horizontal meridional components of the geostrophic sub-surface currents, and in addition the vertical gradient of the horizontal component of velocity is related to the horizontal gradients of the temperature field through

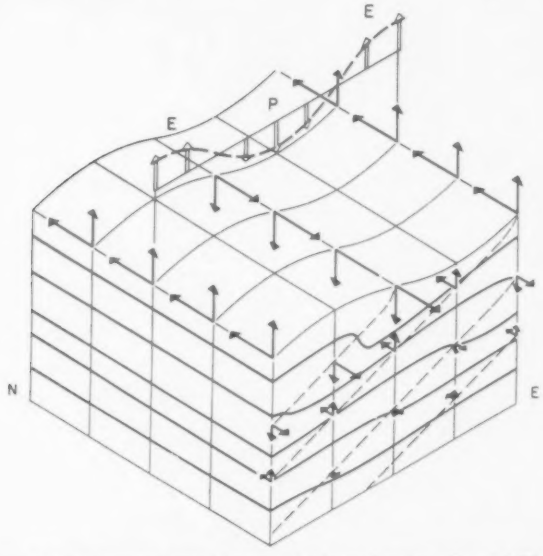

Fig. 14. Modification of the LINEYKIN model caused by introduction of a variable Coriolis parameter. The sloping dashed lines indicate the limits of the regions of positive and negative perturbation temperature (hot and cold cells) ; the rest of the diagram is labelled in the same manner as Fig. 13, but for convenience the model is driven by meridional bands of precipitation and evaporation (the hovering open arrows).

the well-known thermal wind relation. These necessary relations are sufficient to define the entire temperature and velocity fields as shown in Fig. 14. It is interesting to note the asymmetrical distortion of the isothermal surfaces; the maximum perturbation of temperature moves toward the west with increasing depth. If the east-west dimensions of the bands of precipitation-evaporation, or of wind stress, have a wavelength of 6000 km, the vertical eddy diffusivity is 5 cm^2 sec and the mean vertical temperature gradient is 5°C/km, the depth of the maximum amplitude of perturbed temperature lies at about 1000 metres in midlatitudes, and decreases markedly toward the equator. Comparison of different latitudes on the beta-plane is possible by treating the Coriolis parameter parametrically. There is an indication of a rudimentary thermocline in Fig. 14, at about this depth (the thermocline tilts downward toward the west, and one also gets the impression of a tongue-like protrusion of warm water downward and westward, between cold tongues moving upward and eastward. However this is only an illusion, and not at all like a true tongue or

" Kernschicht " because there is no east-west component of velocity anywhere in the model. All motion is confined to vertical meridional planes. Although this model contains eddy diffusivity, it does not contain eddy viscosity.

The physical setup of this model is contrived to make the mathematics easy, consequently the regime does not look much like naturally occurring ones. The distribution of causal agent in parallel meridional bands is clearly an artifice. Over real oceans winds and heating and cooling are much more nearly functions of latitude than of longitude. The LINEYKIN model (Fig. 13) is completely indifferent to a shift of axes of the causal agent, but the model on the beta-plane (Fig. 14) is very sensitive to a shift of axes. If in the latter case the perturbing forces are made functions of latitude rather than of longitude, the meridional components of geostrophic flow vanish, and the flow pattern deepends and is transformed to the LINEYKIN one. In such a case the variation of Coriolis parameter with latitude would enter only parametrically. However, the introduction of a meridional barrier into the model would force strong meridional components of geostrophic flow by making the zonal turn around, and we can anticipate that this would permit the variation of Coriolis parameter to play an important role over a large distance from the coast, a distance possibly as great as the entire width of terrestrial oceans. Thus it seems possible that the vertical distribution of density and currents in a more realistically setup theoretical model (with zonal winds, the beta-plane, and a meridional boundary) might resemble that in the extremely artificial model of Fig. 14. To date it has not been possible to work out the mathematics of such a happier model.

There are more serious drawbacks to these models, however, than superficial similarity to nature. First, the strong vertical stability, uniform with depth, is merely a contrivance that permits a linear perturbation analysis ; it has no counterpart in the ocean. Actually all the heat advective terms in the heat transfer equation must be significant. Secondly, the parametric treatment of the eddy coefficients is exceedingly primitive and misleading. Even if oceanic turbulence at mid-depths is not directly related to the mean flow, it is desirable to have some physical understanding as to what causes this turbulence. At present we simply regard these coefficients as given arbitarily, at best we infer them from water-mass analysis. Our models are, so to speak, externally stirred. And perhaps they actually are, through short internal waves generated by storms. But this is all sheer speculation.

Time variable systems : *Free Waves on a Homogeneous Ocean of Uniform Depth*

The purpose of this section is to give a general description – in physical terms – of the types of free wave motion which are possible on a rotating globe. In order to avoid the almost endless variety of small-scale waves that are discussed in the general hydrodynamic literature, and have no special significance for phenomena of the oceanographic scale, only waves in which hydrostatic equilibrium exists at all times are considered. Thus we confine our attention to dynamical systems akin to those discussed in LAMB's chapter on tidal waves. The reader will note that the term " waves " is used in a somewhat general way, to embrace not only those transient phenomena which are customarily considered examples of hydrostatic wave motion (tides, seiches, long-period internal waves, surges, etc.) but also to include certain transient ocean current systems which propagate themselves in a wave-like manner. Thus the term is used more in the meteorologists' sense – it can include quasi-

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geostrophic disturbances of large-scale circulation systems – or in certain contexts, the largest scale systems themselves, there being no implicit upper limit to the length of the period admitted. On the other hand, certain familiar types of waves, such as ocean surface waves, being of too high a frequency, too small a scale, and not at all hydrostatic, are not considered at all.

First let us consider some of the results of the tidal theorists (HOUGH, as summarized by LAMB, 1932, pp. 349-350) in particular the case of free waves on a homogeneous ocean of uniform depth on a rotating globe. In order to limit discussion only the case of uniform depth of 14,520 feet is considered here, a particular depth being

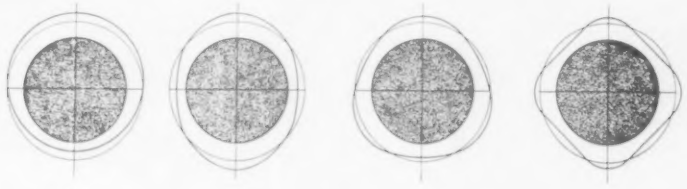

Fig. 15. Four different symmetrical modes of oscillation of the free surface (heavy line) about the undisturbed sea level (light line) on a globe. The figure represents a section through the globe's axis of rotation.

chosen so that numerical values for periods of various waves can be given. In Figs. 15 (a, b, c, d) the deformation of the elevation of the free surface are independent of longitude. In Fig. 15 (a) there is only one nodal circle at the equator, the elevation of the surface seesaws from north to south across the equator in a huge standing oscillation. For the actually rotating earth with depth 14,520 feet the free period of this standing wave across the equator is 25 hr 28 m, but if the earth did not rotate the period would be 41 hr 55 m – it is striking how much the rotation of the earth alters the free period of this large-scale oceanic standing wave, or seiche.

The second case shown, in Fig. 15 (b), has two nodal latitude circles at about 30°N and 30°S. The elevation of the free surface alternates between polar regions and tropical regions. The free period, as might be expected is shorter than for the case with one nodal circle, namely 15 hr 11 m (23 hr 12 m without rotation). Similarly higher numbers of nodal circles lead to shorter periods : thus in Fig. 15 (c), with three nodal circles the period is 11 hr 54 m (16 hr 08 m without rotation) ; or in Fig. 15 (d) with four nodal circles the period is 10 hr 01 m (12 hr 23 m without rotation). As the number of latitudinal nodal circles is increased the effect of the rotation on the period becomes negligible. For example, the case with twelve latitudinal nodal circles has a period of 4 hr 12 m (4 hr 21 m without rotation). This is an illustration of the more general fact that the earth's rotation does not apparently affect wave motions with a frequency much higher than the rotational frequency of the earth (2π radians a day).

Now it is an important thing to note at this point that any one of the configurations of the free surface associated with the axisymmetrical waves drawn in Fig. 15 can also be maintained, within the framework of this simple frictionless dynamical system, with infinite period by an appropriate system of steady zonal geostrophic currents. For example, in Fig. 15 (b) westward flowing geostrophic zonal currents in both

hemispheres would balance the particular deformation of the free surface there depicted.

We will now proceed to describe wave forms which are not axisymmetrical and will find similar geostrophic current systems, which are functions of longitude as well as of latitude, and whose periods are not infinite, but are quite long relative to the period of inertio-gravitational waves with the same shape of the free surface. They are more like wavy current systems such as one encounters in the atmosphere.

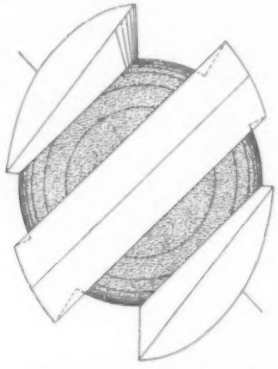

Fig. 16. Antisymmetrical mode of oscillation.

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In Fig. 16 a wave is illustrated in which one complete meridian and the equator are nodes. The ocean is 14,520 feet deep. Consider waves moving east or west : waves in which the equatorial node remains fixed, but the meridional node moves around the earth. The wave toward the east has a period of 19 hr 16 m ; the wave toward the west, 12 hr 51 m (without rotation both waves have the period 23 hr 12 m). Waves of this kind – whose period approaches a finite value as the rotation is decreased toward zero – are called waves of the First Class and correspond physically to what one usually has in mind when he thinks of long tidal waves (this is also true of the finite period waves in Fig. 15).

In addition to the high-frequency First Class waves, there is a nearly geostrophic wave of much the same form (the actual form shown in Fig. 16 is computed from HOUGH's expansion, 1897, II, p. 167) which travels only toward the west) there is no eastward counterpart) and has a period of 11 days. These waves are called Second Class waves by the tidal theorists and are distinguished by the fact that they become stationary (their period becomes infinite) if the rotation of the globe is reduced to zero. As we have seen, in the special case of axisymmetric waves (Fig. 15) the period of of the Second Class motions is always infinite. From a physical point of view these waves of the Second Class are moving current systems. In the presence of a basic zonal current waves of the Second Class may be identified with ROSSBY's planetary waves (ROSSBY, 1939). The Second Class waves are essentially the building blocks from which the general forced wave motions characterizing the transient ocean current theory are constructed. One more example of free wave motions on the sphere may be of interest to mention. GOLDSBROUGH (1933) has obtained the free periods of waves in a homogeneous ocean of uniform depth (12,880 ft) bounded by meridional coasts 60° apart. In addition to two First Class waves (rotary tidal waves with periods

12 hr 25 m and 10 hr 18 m) he has also found a Second Class wave with a period of 7·2 days. This wave might be spoken of as a free quasi-geostrophic seiche. One supposes that the Atlantic Ocean must be somewhat resonant to weekly periods of atmospheric disturbance. The successive elevations of the free surface characterizing this Second Class standing oscillation of GOLDSBROUGH are sketched in Fig. 17 : only the first quarter period is illustrated.

Fig. 17. Sketch of successive contours of surface level in GOLDSBROUGH's 7·2 day geostrophic standing wave (Second Class) in an ocean bounded by meridians 60° apart ; only the first quarter period is depicted.

It is much more convenient, in trying to obtain a clear physical understanding of the differences between the First and Second Class waves, and in working out simple mathematical examples, to abandon the co-ordinate system of the sphere, and to make use of a plane system of co-ordinates, introduced by ROSSBY (1939) in which the variation of the Coriolis parameter is taken as a constant over the plane, and the Coriolis parameter itself is also taken as a constant wherever it occurs in undifferentiated form. This so-called beta-plane has been widely adopted in dynamical meteorology on account of analytical advantages and the simplicity of physical interpretation of the phenomena which it exhibits. On the other hand, one should keep in mind the fact that the beta-plane is not a perfect analogue of this sphere.

Consider now free harmonic waves propagated along the east-west direction with horizontal crests and troughs parallel to the north-south axis, as sketched in Fig. 18 (a-f). The undisturbed depth is uniform and the water homogeneous. Hydrostatic equilibrium prevails; the pressure gradients are independent of depth and depend only upon the instantaneous slope of the disturbed surface (remember the vertical scale in the diagrams is much exaggerated). Thus the horizontal components of velocity are independent of the vertical co-ordinate. The vertical component of velocity varies linearly with depth in such a manner as to vanish at the bottom and to equal to time rate of change of surface elevation at the top of water layer. For any wavelength there are three possible such waves on the beta-plane. Two are First Class; one, Second Class. A so-called frequency diagram is sketched in Fig. 19. The ordinate is frequency, the abscissa wave number or reciprocal wave length. THOMPSON (1952) has given a very clear review of the theory of these different waves. We will content ourselves here with a simple physical description. The curve marked I in Fig. 19 corresponds to First Class Waves which can move either towards the east or the west. They have relatively high frequency, and are simply the familiar long gravitational-inertial waves. For short wavelengths (region 1 in Fig. 19) the First Class waves are unaffected by the earth's rotation, are ordinary long gravitational or tidal waves, and are non-dispersive. The particle orbits are indicated in Figs. 18 (a) and 18 (b). Particles move in straight-line segments (neglecting the very small vertical displacements) alternately toward the west and east, the maximum horizontal velocity

being toward the direction of wave propagation under a crest, and in the opposite direction under a trough. For longer wave lengths (region 2, Fig. 19) the First Class waves are dispersive, and the period approaches half a pendulum day. These waves were first discussed in detail by SVERDRUP (1927), in connection with tides on the North Siberian Shelf. In addition to the back-and-forth particle motion in the direction of wave propagation, there are also components of horizontal motion transverse to the direction of wave propagation, so that the particles execute elliptical orbits,

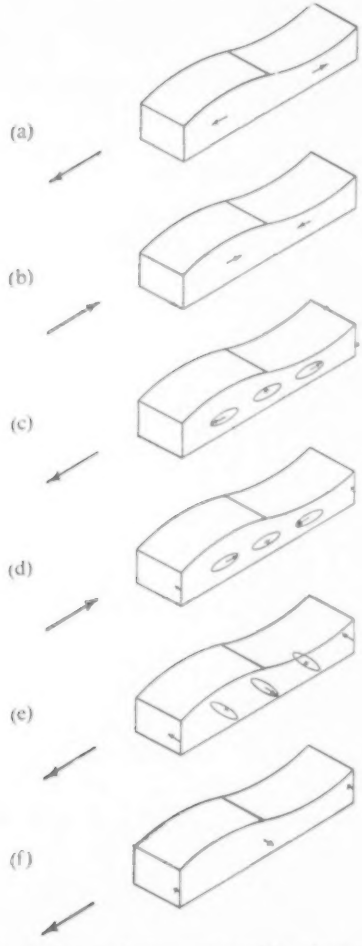

Fig. 18. Sketch of surface perturbation, instantaneous particle velocity (arrows), hodograph (ellipses) for different kinds of free long waves. The arrows on the left show the direction of propagation. By convention we take left ward as westward.

(Fig. 18c, d) which, as the frequency approaches half a pendulum day, tend to become circular – the limit particle motion in pure inertial circles. Density stratification introduces free internal modes, which, for a given wavelength are much more affected by the earth's rotation (VERONIS and STOMMEL, 1956), but it would be too much of a

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digression from the main theme of this review to consider First Class waves much further here.

The second curve in Fig. 19, marked II, gives the frequency vs. wave length relation for Second Class waves in the homogeneous ocean on the beta-plane (ROSSBY 1939). There are two distinct regions to the curve : a long wave length region (region 3 in Fig. 19) with long periods, the waves being non-dispersive, and another region (region

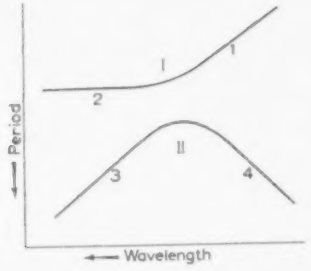

Fig. 19. Period-wave length relation for First Class (I) and Second Class (II) waves in a homogeneous layer on the beta-plane.

4 in Fig. 19) of shorter wavelengths, also of long period. These short waves are highly dispersive, and interesting enough are of such a nature as to have very little horizontal divergence. The two regions 3 and 4 are connected by a shorter period transition region. The minimum period of Second Class waves appears in this transition region. The free waves of Second Class move only to the west. The orbits are essentially horizontal ellipses with major axes parallel to the crests, as shown in Fig. 18 (e). The particle orbits become more and more eccentric as the period increases, for both long and short wavelengths (Fig. 18f). It is clear that the Second Class waves are essentially geostrophic current systems which because of the planetary geostrophic divergence inherent in the beta-plane cannot remain stationary. Consider the Second Class wave shown in Fig. 18 (f). The current is toward the south and the Coriolis force is balanced by the eastward horizontal pressure gradient due to the slope of the free surface. The divergence of this geostrophic current can be balanced in two ways : (1) first, the free surface can drop over southward currents and rise over northward ones (northern hemisphere) – which leads to the non-dispersive westward propagation of the wave form indicated by region 3 in Fig. 19; (2) the southward current is subject to an increase in relative vorticity, the elevation of the free surface producing negligible divergence, and northward current suffer a decrease in relative vorticity, thus shifting the vorticity pattern toward the west as indicated by the region 4 in Fig. 19. The transition region in Fig. 19 combines both these effects.

Two free progressive Second Class waves of the same frequency can also be combined to permit reflection from a meridional barrier (ARONS and STOMMEL, 1956). Both the waves move in the same direction of course, but the group velocity is opposite for the incident and reflected wave, and there is no net energy flux. If the homogeneous water layer is bounded on both the east and west by meridional walls there are only certain discrete free frequencies allowed – an eigenvalue problem which gives the free Second Class periods of closed basins.

Free Second Class waves in a density-stratified system

The introduction of vertical density stratification in the model permits internal or baroclinic modes of both First and Second Class. The periods for a given wavelength are much longer than for the external or barotropic mode. Since the frequency

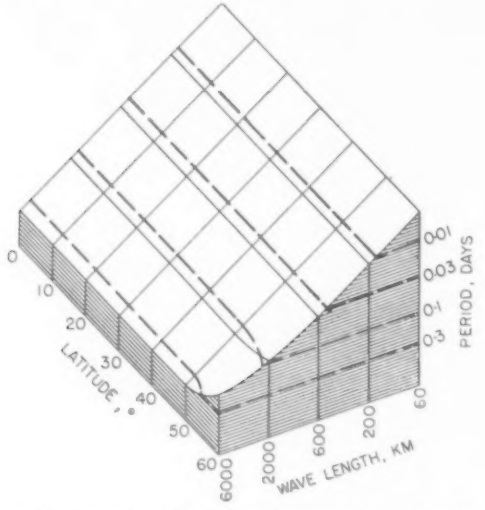

Fig. 20. Periods of First Class barotropic ocean waves.

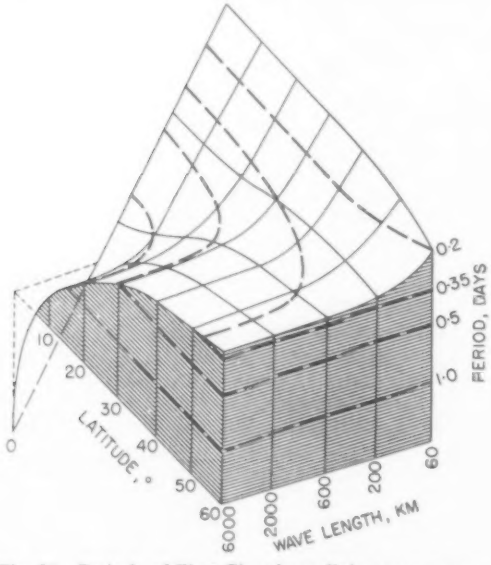

Fig. 21. Periods of First Class baroclinic ocean waves.

diagram of these different classes and modes is partly a function of latitude, and of density structure, a single curve will not be very helpful. Therefore I have prepared four block diagrams that give periods of free waves as a function of latitude and

wave length for the cases : First Class barotropic, Fig. 20 ; First Class baroclinic, Fig. 21 ; Second Class barotropic, Fig. 22 ; and Second Class baroclinic, Fig. 23. The baroclinic diagrams are prepared by using a two density layer model (VERONIS and STOMMEL, 1956) with thickness of the layers and density difference chosen to

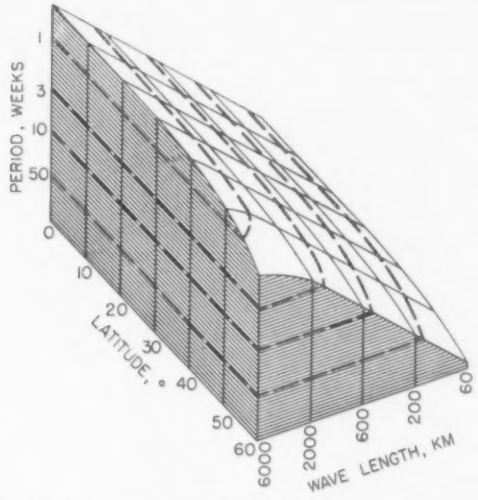

Fig. 22. Periods of Second Class barotropic ocean waves.

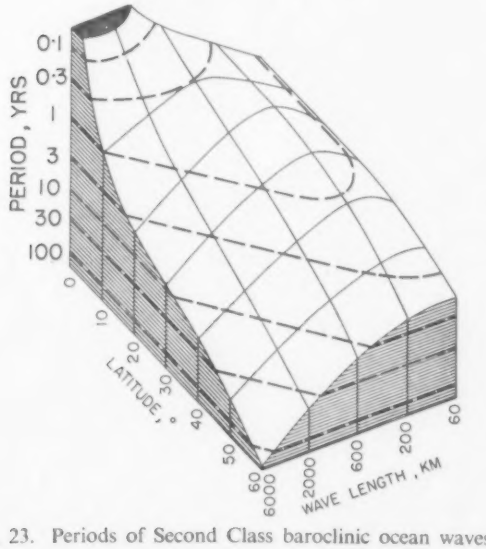

Fig. 23. Periods of Second Class baroclinic ocean waves.

match as nearly as possible that of the North Atlantic for each latitude. The barotropic diagrams are prepared using representative depths of the North Atlantic. Hence the diagrams are not quite as smooth looking as they would be if computed entirely from a single geometry and density difference.

The Second Class barotropic waves have periods, for wavelengths corresponding to oceanic dimensions, of about a week. Second Class baroclinic waves of oceanic dimension have very long periods ; only near the equator is there a period as short as a year, however it should be remembered that the approximations in the beta-plane are bad at the equator, so that the results there must be received with caution.

Transient response of the ocean to a variable driving force

The properties of free waves in a two-layer stratified fluid on the beta-plane are helpful in understanding physically the response of a stratified system to changes in the driving system. Quantitative theoretical studies of the response to changing forces are rather involved, and it seems fruitless to try to explain them verbally. A set of references to work in this field is given in another place (VERONIS and STOMMEL, 1956). In this brief review article we must be satisfied by a brief statement of the main results of the theories.

First of all, very short period or abrupt changes in the driving forces such as earthquakes, or sudden storms over shallow seas excite mainly the First Class barotropic mode. VERONIS (1956) has shown that when the interval during which an applied wind stress is changed from one value to another exceeds a half pendulum day most of the work done by the wind stress upon the sea goes into Second Class waves, that is, into currents. If this interval during which the wind changes is smaller, energy goes into First Class wave motions. Within the Second Class motions themselves the distribution of energy between barotropic and baroclinic modes depends very much upon whether the period of the forcing function is closer to the barotropic free period corresponding to the wave length of the forcing function. Thus in midlatitudes a large-scale storm of dimensions 600-2000 km and duration of three to five days will excite the barotropic mode of the Second Class. The Second Class baroclinic mode is also excited, but its amplitude is much smaller than would be expected were the storm to become stationary and to blow constantly for a long time. This can be seen by comparing Figs. 22 and 23. The currents produced will be largely independent of depth (beneath the surface friction layer of course) and the thermal structure of the ocean will not be much influenced. On the other hand in low latitudes a large scale fluctuation of the winds with a period of a year (for example, the Indian Ocean Monsoon) will nearly be in resonance with the Second Class baroclinic mode, as can be seen from Fig. 23. Hence in this case the currents responded chiefly in the upper layer, and the density structure changes markedly to accommodated them. In high latitudes seasonal changes in the winds are not so near to resonance with the Second Class baroclinic mode ; for example one might expect the Antarctic Circumpolar Current to show little seasonal change of deep thermal structure due to seasonal wind changes.

In a simple two-density layered ocean in a closed basin the steady state vertically integrated transport is given by the SVERDRUP solution. If there is no mass transport or mixing across the interface, all the steady motion is in the upper layer. If the wind-stress distribution is now changed, from one pattern to another, on an oceanic scale, the vertically integrated transport distribution adjusts itself to that corresponding to a new steady state distribution within a few weeks ; but the vertical distribution of velocities is very different from that of the final steady state. The simple two-layer theory indicates that several years or decades (in midlatitudes) are necessary before

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the vertical distribution of velocities approaches that of the steady state solution with all the velocity in the upper layer. Thus we see that the total vertically integrated transport responds rapidly to changes in applied wind stress, but the internal density field responds quite slowly. The response of the internal density field is not governed by the period of inertial-gravitational (First Class) waves, as is sometimes thought by hydrographers, but by the much longer period Second Class internal waves.

As another illustration, this time a hypothetical one, imagine a two-layer ocean completely at rest. The surface and the interface are horizontal. Now suppose that a constant convergent EKMAN wind-driven layer with maximum convergence at the midlatitude of the diagram (Fig. 24 a, b, c) is superposed at the surface in such a manner that the response of the ocean is mostly in the Second Class baroclinic mode – in particular, the large wavelength non-dispersive portion of the frequency diagram.

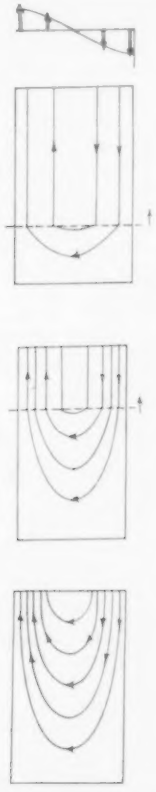

Fig. 24. Three successive stages of the slow development of the steady deformation of the thermocline from rest by a wind stress distribution as shown at the left. The dashed line is a " front " moving slowly (a mile a day) from the eastern coast to the western coast. On the left of the front the thermocline steadily deepends; on the right it is stationary in the SVERDRUP manner (Fig. 12).

Under these circumstances the first response of the interior of the ocean is a simple deepening of the interface at a constant rate equal to the supply of water at the surface from the EKMAN layer. Near the coast there is a sharp transition from this simple response of the interior to a configuration of the interface characteristic of the steady

state solution which would exist had the wind blown forever (Fig. 12). The region of transition from one type of solution to the other slowly moves westward until the entire ocean is covered by the steady state solution. Two successive stages of this development and motion of the discontinuity between types of solution are drawn in Fig. 24 (a, b, c). One assumes that the whole process is so slow that at every stage of development there is a western current equilibrium at the western boundary that is able to cope with the need for a western boundary condition.

The stability of the solutions and the dilemma of the Antarctic circumpolar current

One of the most unsatisfactory aspects of the theoretical solutions so far developed in oceanography is the fact that they have not been exmined for stability. Dynamical meteorologists are convinced that a steady state model does not apply to the atmosphere except possibly in the Trade Wind regions. Elsewhere large quasigeostrophic wave disturbances appear and disappear spontaneously in the zonal wind systems and play a very important dynamical role in the general circulation of the atmosphere. Some investigators even believe that disturbances maintain the zonal flows. Should this be the case, it is obvious that steady state models incorporating large arbitrary lateral eddy coefficients would scarcely be very enlightening. By analogy with developments in the study of meteorology, oceanographers are warned to employ steady-state theories of the ocean with caution – especially models which employ large-scale eddy coefficients. In the tropics and subtropics the SVERDRUP theory seems to apply quantitatively to the ocean circulation, although there is not sufficient observational material for a completely convincing demonstration one way or the other. This suggests that the SVERDRUP model is essentially stable in the tropics, but we are far from a mathematical demonstration of its stability. In general it seems to me that we might expect theoretical models of oceanic circulation to be much more stable than those of the atmosphere on account of the presence of the meridional barriers because the high velocity zonal currents characteristic of instability in the atmosphere are suppressed by the coasts. This is, of course, sheer speculation.

A numbers of authors (e.g. MUNK and PALMEN, 1951) have pointed to the Antarctic Ocean as an example of an ocean without meridional barriers, and as such one in which a SVERDRUP type solution cannot be constructed. In an ocean without meridional barriers there can be no net meridional component of geostrophic flow, and we are forced back to circulations like the HOUGH regimes. A very crude model of the Antarctic Circumpolar Current can be constructed by employing lateral viscosity. Several Japanese authors (HIDAKA and TSUCHIYA, 1953, and others) have constructed models of the Antarctic Circumpolar Current as essentially a laterally viscous zonal stream driven by the southern hemisphere westerlies. In order to limit the total transport of the Circumpolar Current to about 100×10^6 m^3/sec a lateral eddy viscosity of more than 10^{10} cm^3/sec is required – several orders of magnitude greater than that generally envisaged in other oceanic currents. If vertical viscosity is employed very large coefficients are also required. On the other hand, the fact that the deep warm water in the Circumpolar Current preserves its Atlantic characteristics even into the Pacific Ocean suggests that the lateral diffusivity can hardly exceed 10^7 cm^2/sec, nor the vertical diffusivity be much greater than 10 cm^2/sec. Thus the implications of water-mass analysis are not compatible with the large turbulent coefficients required in the purely zonal and frictional theory.

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There have been several other mechanisms suggested for the Antarctic Circumpolar Current (MUNK and PALMEN, 1951; FOFONOFF, 1955) all of which regard it as a purely zonal phenomenon. The cross section of the channel between the Cape of Good Hope and Antarctica is quite broad and deep (Fig. 25a), and a section straight from Cape Horn and Graham Land is also quite adequate (Fig. 25b) to permit the

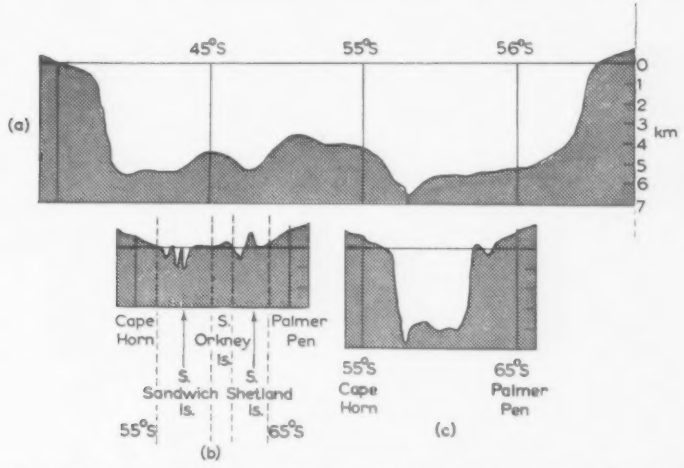

Fig. 25. Depth profiles across the Southern Ocean : (a) From Cape of Good Hope to Antarctica ; (b) From Cape Horn to Palmer Peninsula ; (c) Minimum depth of each latitude circle.

Circumpolar Current to pass through. However, if one plots the minimum depth for each complete latitude circle, it is found that the latitude circles that pass through Drake Passage are blocked by the island arc somewhat to the east. The minimum depths are plotted in Fig. 25 (c). It is seen that nowhere in the Antarctic Water-Ring is there a latitude with a deeper threshold than 1000 m. The Antarctic Circumpolar Current therefore cannot be purely zonal. In fact (DEACON, 1937) there seems to be a general southward component of the current over the entire southern ocean except just after passing through Drake Passage, where it is deflected sharply north by about 10° of latitude in a very limited narrow region, and possibly also to some extent just after passing New Zealand. Now if there is anything to this picture it suggests that the Antarctic Circumpolar Current is essentially amenable to treatment by the SVERDRUP theory; that the current is essentially frictionless except in a narrow region just after it passes through Drake Passage. In this one limited region we anticipate that all the dissipation of energy, any instability, and higher order processes occur. The remarks which follow cannot be considered to be a theory; they are merely suggestive of one, and they do illustrate some of the physical ideas described in this survey.

Before attempting to interpret the internal modes of circulation, we first consider only the vertically integrated flow – it is only necessary to consider a simple homogeneous ocean of uniform depth. In order to proceed simply we first consider that Drake Passage is closed (Fig. 26a). This barrier is indicated by the heavy radial line in the figures, joining the schematic Antarctic continent. The assumed zonal wind system is shown in Fig. 26 (a). Trades from the Equator to 30°S, westerlies from 30°

to a little over 60°S, and further to the south a small zone of Easterlies. The EKMAN drift is northward in the westerlies, southward in the easterlies. South of about 50°–55°S the EKMAN drift is divergent, in more northerly latitudes it is convergent. According to our simple physical notions we expect this divergence to be compensated by the planetary divergence of meridional components of geostrophic flow. There is no difficulty in obtaining such a flow in the ocean of Fig. 26 (a) because there is a

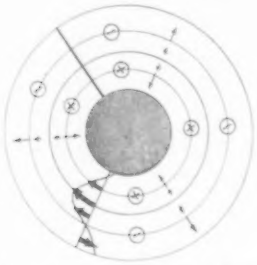

Fig. 26 (a). The schematic Southern Ocean. Antarctica is the solid black circle. The meridional barrier extending northward from Antarctica is represented by the solid heavy black vertical line. The schematic wind system (purely zonal) is depicted by the heavy arrows on the lower left. The concentric circles are latitude circles. Latitudes of EKMAN convergence and sinking at the surface are indicated by minus signs, latitudes of EKMAN divergence and upwelling are indicated by plus signs. The direction of the required meridional geostrophic flow is indicated by light radial arrows.

Fig. 26 (b). Transport lines of the solution for the model depicted in Fig. 26 (a). The western boundary currents are to be interpreted schematically.

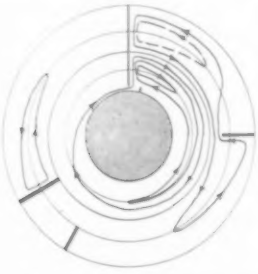

Fig. 26 (c). Modification of the transport field produced by introduction of other meridional barriers corresponding to Africa, Australia, and New Zealand, and by breaking the American-Antarctic barrier so as to admit a very constricted Davis Straits.

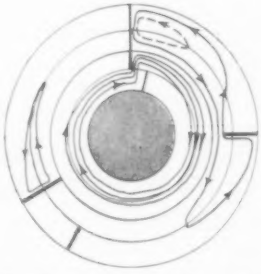

Fig. 26 (d). Hypothetical form of the solution that results from rupturing the American-Antarctic barrier in such a way as to permit water to flow through, but to obstruct all latitude circles.

complete meridional barrier. The necessary meridional components are shown by heavy arrows in Fig. 26 (a). The full transport field is developed by continuity from the eastern side of the ocean (western coast of South America) and fitted with an intense western boundary current at the western coast of the ocean. There are two immense gyres in Fig. 26 (b). wrapped around the world parallel to latitude circles. A simple calculation shows that the transport in the southern gyre amounts to somewhat more than 100×10^6 m^3/sec, the northern gyre somewhat less. Thus

each line in Fig. 26 (b) is roughly 30×10^6 m^3/sec. Actually the northern gyre is broken up by the African and Australia-New Zealand continents so that it must be modified in some such way as indicated in Fig. 26 (c). In this figure a small breach has been made in the South America to Antarctica barrier, enough to permit one transport line to pass through, otherwise the general shape of the southern gyre is not much altered. If the barrier is broken in a manner indicated in Fig. 26 (d), so that there is no unbounded latitude circle, but there is a pass for water to flow through to the north, it seems to me that the pattern of flow must then look something like drawn. This picture is obtained by keeping all mid-ocean transport lines north of the latitude of the passage just the same as in Fig. 26 (b), but south of this latitude by developing the transport function from the western coast of the ocean (the east coast of the Palmer Peninsula) toward the east. The flow through the passage itself is something of a mystery, but doubtless models can be devised to describe it. Due to the extreme elongation of the flow pattern illustrated in Fig. 26 (d) the current looks like a purely zonal one at first glance. The over-all agreement of this picture with the lines of equal dynamic height in DEACON's study (1937) is fairly striking. Thus we see that there is some reason to suppose that the Antarctic Circumpolar Current is not such a dynamical misfit as originally it was thought to be. One need

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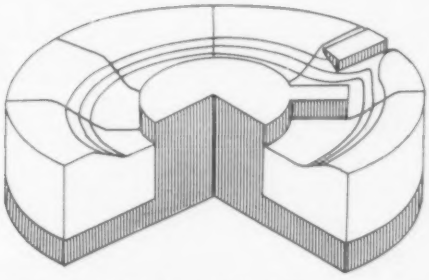

Fig. 27. Surface contours (or isobars) of the hypothetical Circumpolar Current shown in Fig. 26 (d).

merely recognize that it is not a zonal current after all. Fig. 27 shows the homogeneous model in perspective. The transport lines are parallel to the surface height contours everywhere except in the narrow passage where they cross isobars in a downhill direction. A water particle does not drop the full dynamic height difference across the Antarctic Circumpolar Current each time it makes a circuit around the world, but requires from three to five circuits on the average it drops the full dynamic height and rises to the surface, and is carried away to the north across the latitude of maximum westerlies in the surface EKMAN layer. The EKMAN northward transport is non-geostrophic, and distributed all around the southern ocean ; it is indicated by the radial arrows in Fig. 28. For entire 55°S latitude circle it must amount to at least 20×10^6 m^3/sec. This is the latitude of maximum westerlies, and there is no mid-ocean meridional flow where the EKMAN layer is non-divergent. There is a western current on the western coast of the ocean (eastern South America) setting southward, and just to the north of Drake Passage. Thus it is that the water which replenishes that lost to all the oceans north of 55°S by the EKMAN layer, is drawn mostly from the South Atlantic western trough. There is reason to suppose that this supply is largely Atlantic Deep Water.

The actual Antarctic circulation is partly baroclinic. We now proceed to make a crude interpretation of the internal structure of the flow. In Fig. 28a schematic diagram of the southern ocean is presented, showing the Antarctic continent as the central cylinder, and the American Barrier with Drake Passage indicated to the right. Two level surfaces intersect the body of the ocean: L_1 at a depth of approximately 600 and L_2 at a depth of about 3500 to 4000 meters. Let us now specify the vertical transfer across these levels. Across level L_1 there is a general upward flux of mass from the warm deep layer, apparently almost enough to compensate for the water lost by the upper layer to the divergent EKMAN layer on the very top. Across level L_2 there is very little vertical transfer, except near the Weddell Sea where some Antarctic Bottom Water sometimes sinks across it. The Bottom Water cannot flow anywhere to speak of except up the western coast of the ocean in a narrow western boundary current beneath L_2, because the rest of the layer is non-divergent. The whole of the large body of warm saline water between level L_2 and L_1 is apparently convergent on account of the flux upwards across L_1. As we have seen, a system of this sort can develop a strong geostrophic component of flow everywhere in mid-ocean by spiralling in towards the Antarctic Continent except for the abrupt northward displacement that occurs in Drake Passage. The supply of water for this main body of the Circum-

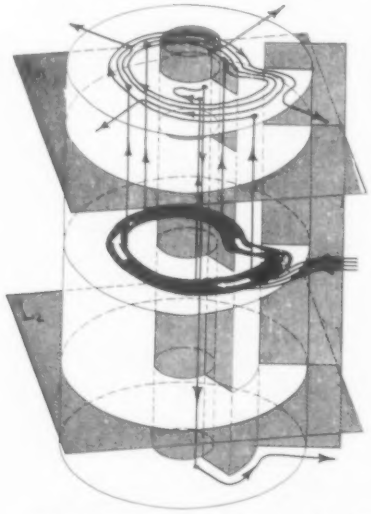

Fig. 28. Schematic three-dimensional diagram illustrating the hypothetical schematic internal structure of the Circumpolar Current (see text for detailed explanation). Two reference levels, L_1 and L_2, intersect the body of the ocean. The central shaded cylinder is the Antarctic Continent. The vertical plane attached to it at the forward right is Palmer Pensula, and the detached vertical plane at the extreme right is South America. The curved lines with arrow heads are transport lines. In order to avoid complicating the diagram, the more realistic spiralling motion is not shown.

polar Current comes from a narrow stream of Atlantic Deep Water flowing, as western boundary current, down the west side of the South Atlantic Ocean. In the layer between 600 m and the bottom of the EKMAN layer it is not clear just how to interpret the state of affairs. If this layer is slightly convergent it should move more or less along with the deep water ; if it is non-divergent – that is, loses as much to the EKMAN layer as it gains from the warm deep layer, it may move more nearly

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zonally than the deep water, because it is not so completely blocked by the island arc from attaining zonal flow, or if it is divergent it may drift northward everywhere with the surface EKMAN drift. The simple picture shown in Fig. 28 does not extend north of the Antarctic Convergence, so no attempt is made to interpret the formation of Antarctic Intermediate water, etc.

Finally I should like to make an apology for ending this survey article with such a sketchy and incomplete interpretation of the Antarctic Circumpolar Current as I have just given above. I should have hesitated to do so were it not for the fact that it so clearly illustrates both the usefulness and weakness of the physical ideas reviewed above.

Acknowledgements—I am particularly indebted to Mr. GALE PASLEY for drafting some of the intricate diagrams in this article, to Dr. G. VERONIS and Dr. G. MORGAN for many discussions during the past year, and to the Office of Naval Research for underwriting my studies.

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Geophysical studies in the Arctic Ocean

A. P. CRARY and NORMAN GOLDSTEIN

(*Received* 7 *May* 1957)

Abstract—Studies of Arctic Ocean depths along the path of the floating ice-island, T-3, show a prominent ridge rising in one area to 1450 m below the sea surface. This ridge runs parallel to the Lomonosov Ridge and appears to terminate on the northern flank in an escarpment about 1300 m high. Except for this area of rough bottom topography, the depths in the vicinity of the 90° meridian are generally between 1500 and 2700 m with some scattered peaks, possibly of volcanic origin. The continental slope was crossed 100 km off the coast of northwestern Ellesmere Island, with ocean depths decreasing from 1700 to 500 m.

Seismic reflection data were used not only for obtaining the depths of the water but also for finding the character of the sub-bottom reflection horizons. These deeper reflections, though limited to a few kilometres below the ocean bottom, gave information on the uniformity and conformity of the ocean sediments. A widespread quiet reflecting zone extending from about 100 to 300 m below the ocean floor was encountered in the southern half of the area studied. This showed remarkably constant thickness.

The velocity of the bottom sediments, as determined in several locations, ranges in value from 1·6 to 2·4 km/sec. At one site on the slope of the prominent ridge a velocity of 3·77 km/sec was found at the ocean bottom. Though refraction distances were limited to 13 km because of the length of the ice island, in one area a velocity of 5·96 km/sec was found at 1320 m below the ocean bottom.

Gravity values were obtained along much of the path of T-3, with resulting free-air anomalies ranging between − 40 and + 54 milligal. Accurate density delineation of special features was impossible since lack of systematic depth information limited the accuracy of bottom contours.

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INTRODUCTION

THE occupation of the ice island T-3 by the United States Air Force, for the purpose of establishing in the central part of the Arctic Ocean an upper air rawinsonde weather station and for conducting certain other scientific studies, extended from March 1952 to May 1954. During this period the island drifted from 88° 00′N, 156°W to 84° 40′N and 81°W. Because of the proximity to the land-based weather station at Alert, Ellesmere Island, operations were suspended in May 1954. The island was occupied by a small geophysical party without the upper air weather station from April to September 1955, during which time it drifted from 83° 37′N, 88°W to 82° 19′N and 98°W. The general path of the island drift is shown in Fig. 1.

Geophysical studies were carried out by personnel from the Air Force Cambridge Research Center throughout the island occupation with the exception of the period between October 1953 to March 1954. The ocean bathymetry, seismic reflections, seismic refractions and gravity results are to be discussed here. A preliminary note (CRARY, 1954) gave the general bathymetric results in the April 1952 to October 1953 period.

The equipment used for the seismic work was a combination of several individual units : a Heiland Research Corporation twelve-galvanometer oscillograph, Century Geophysical Corporation amplifiers, and geophones made by the Century Geophysical Corporation and the Electro-Techniçal Laboratories. Special low-frequency vertical

Fig. 1. Path of ice-island drift, April 1952 to September 1955.

seismographs made by the Stanley Aviation Company from a design of the Department of Terrestrial Magnetism, Carnegie Institute of Washington, D.C., were also used.

The gravity meter, North American Geophysical Company meter No. 113, was in use during four periods. Unfortunately, it was out for a special calibration during the period from June 1952 to October 1952 when many of the most interesting ocean bottom features were crossed. The gravity reference station was at Thule Air Base in Northwest Greenland.

The Arctic Ocean, because it is ice covered, provides several opportunities for observations which are difficult or impossible to make in an open ocean. The seismic soundings were made off the island edge on the ice pack which was about 2 to 4 m thick. The seismic detectors were generally located in a two-dimensional array up to 300 m on a side although at one time three detectors in a 1200 m line were used for special studies. Though the refraction results were not extensive, shots were fired at distances up to about 13 km as determined by conventional survey methods. Also, the gravimeter readings were made at regular intervals at the camp site. The vertical accelerations of the island introduced no appreciable error, since the readings were generally made at five-second intervals over periods much longer than the general island acceleration periods.

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The island locations were made from star or sun altitude observations with an engineering transit accurate to one minute. The accuracy of locations was quite variable, depending on the weather conditions. In the winter months when three or more star shots could be obtained within a half hour, the error in location was less than one kilometre. In the summer when sun shots were necessary, the weather conditions were generally quite poor. Most difficulties were experienced in periods of storms of several days when the island drifted up to 12 km per day and blowing snow or clouds would prevent necessary solar or stellar observations. The locations of the seismic depth soundings were found by extrapolation between the astronomical fixes. In many cases of sporadic drift, use was made of wind data or ocean-current records but even with this added information some depth locations may be in error by as much as 5 km. In the areas of rapid changes of depth this made contouring quite difficult. Although locations were not always known to necessary accuracies, the directions to true north, which varied quite slowly even with relatively rapid horizontal movement, were considered accurate to a few degrees at all times. Thus, the bottom dip and strike directions where dips were greater than two or three degrees, are quite reliable. Without this dip information, contouring would have been quite inaccurate in many areas. As the island approached the North American continent, bottom slope became considerably smaller and less use was needed for this dip information.

The wave velocities used in the computation of depth were taken from the Kuwahara Charts (KUWAHARA, 1939), using known Arctic Ocean salinities and temperatures. These latter are extremely stable throughout most of the central Arctic Basin and can be considered constant throughout the year. The average velocity values used were as follows, where T represents total travel time :

$$\bar{V}\,(\text{m/sec}) = 1442 + 6{\cdot}8\,\text{T} \qquad T > 3{\cdot}5 \text{ sec.}$$

$$\bar{V} = 1443 + 6{\cdot}7\,\text{T} \qquad 3{\cdot}5 > T > 1{\cdot}7 \text{ sec.}$$

$$\bar{V} = 1437 + 11.0\,T \qquad T < 1{\cdot}7 \text{ sec.}$$

For bottom dip and strike information, straight line ray-path theory was used with the average velocities given above. For sub-bottom dip and strike information, a sediment velocity of 3·0 km/sec was assumed, even though in many cases, as will be noted, this figure is not realistic.

For the refraction studies, curved ray-path effects were calculated on the basis of water velocity variations with depth. The curved ray-path differences in the range of distance used resulted in an addition to the average velocity of approximately 1 m/sec multiplied by the ratio of distance to depth.

GENERAL BATHYMETRIC RESULTS

Figs. 2, 3, 4, and 5 show the detailed bathymetric results with indicated strike and dip where these were obtained and were more than a degree or two. Fig. 6, in which these maps are combined, shows the complete area covered, extending from the continental shelf off northern Ellesmere Island to the North Pole region. Fig. 7 shows the section along the 90th meridian from Ellesmere Island to the North Pole, and illustrates the principle features that are detailed on the maps. It will be noted that the continental shelf extends out 100 km from shore with water depths of about 500 m at the edge. This drops off at about a 3° slope to 1200 m, followed by a more gradual drop to a low of 1700 m. A gradual rise to 1500 m follows then a drop to a low of 2700 m about 525 km off shore. From this low, water depths decrease rather rapidly to an extensive ridge which is a dominant feature of the northern part of the area explored. This ridge, with highest point around 1400 m below the sea surface ends abruptly to the north in an escarpment with a drop of about 1300 m and slope angles of 10° to 15°. The rise out of the valley begins almost immediately along the 90th meridian but further to the west the valley widens in an abyssal plain about 50 km wide. North of the valley across the whole area, a rise of varying slope was found, though the top was not reached along the drifting route of the island. This northerly ridge, parallelling the first, has been termed the Lomonosov Ridge by the Soviets who located it during extensive aircraft landing operations in 1950 and 1951. Details of this vast feature were first revealed at a conference at the Arctic Scientific Research Institute in 1954. The southern parallel ridge, discussed here, appears to be almost as high as the Lomonosov Ridge but perhaps not as extensive. It is proposed that this ridge be named the " Marvin Ridge " after ROSS G. MARVIN who lost his life in the Arctic Ocean during support of PEARY's 1909 trip to the North Pole.

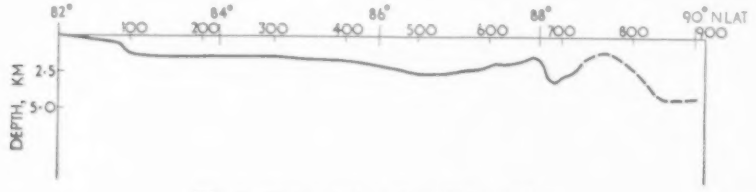

Fig. 7. Cross-section along 90° meridian.

Fig. 2, at the far western side of the area where T-3 was first occupied, shows parts of both ridge systems with a broad abyssal plain between. In the extreme northwest very steep south dips were suddenly encountered following monotonously regular

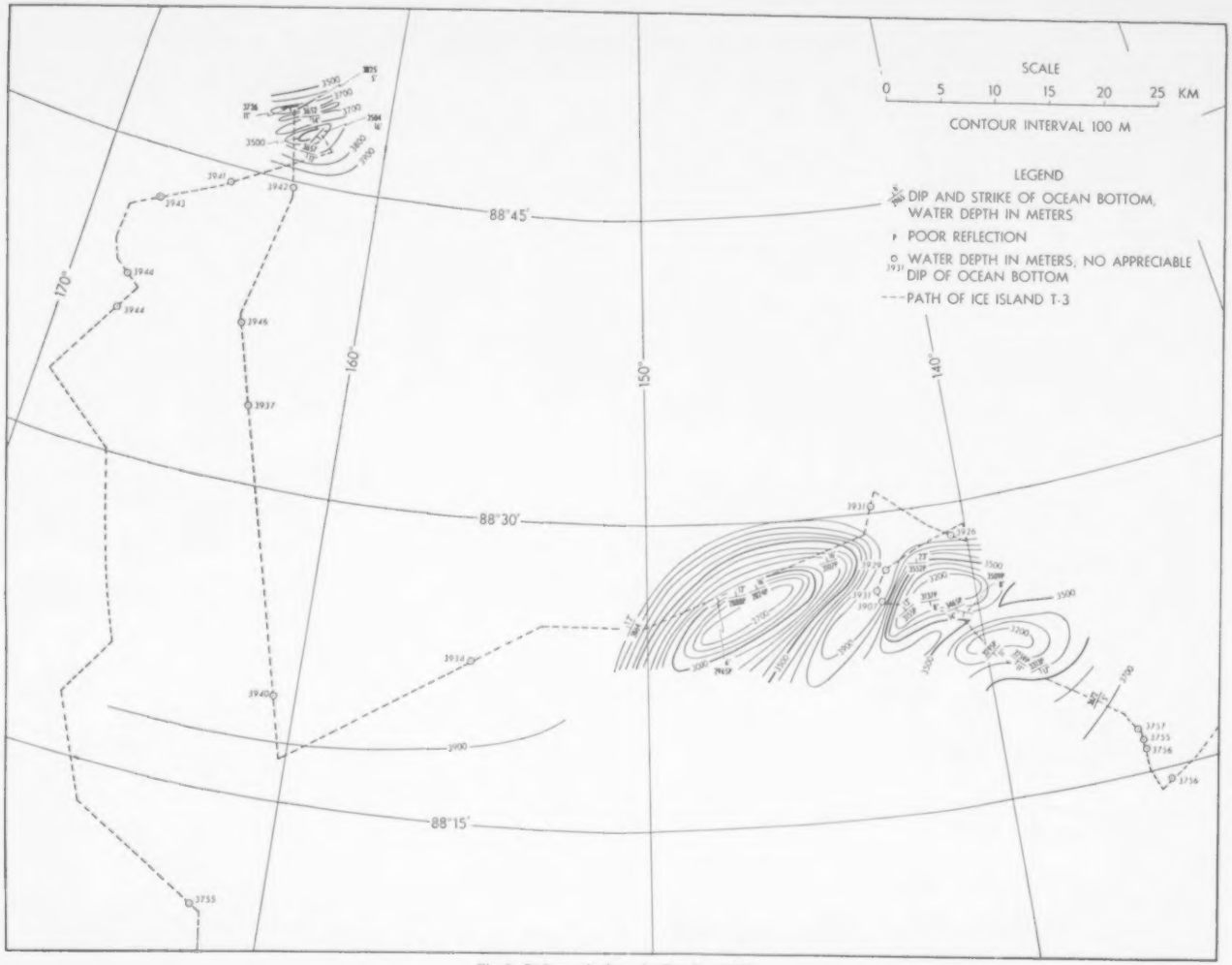

Fig. 2. Bathymetric chart, April to June 1952.

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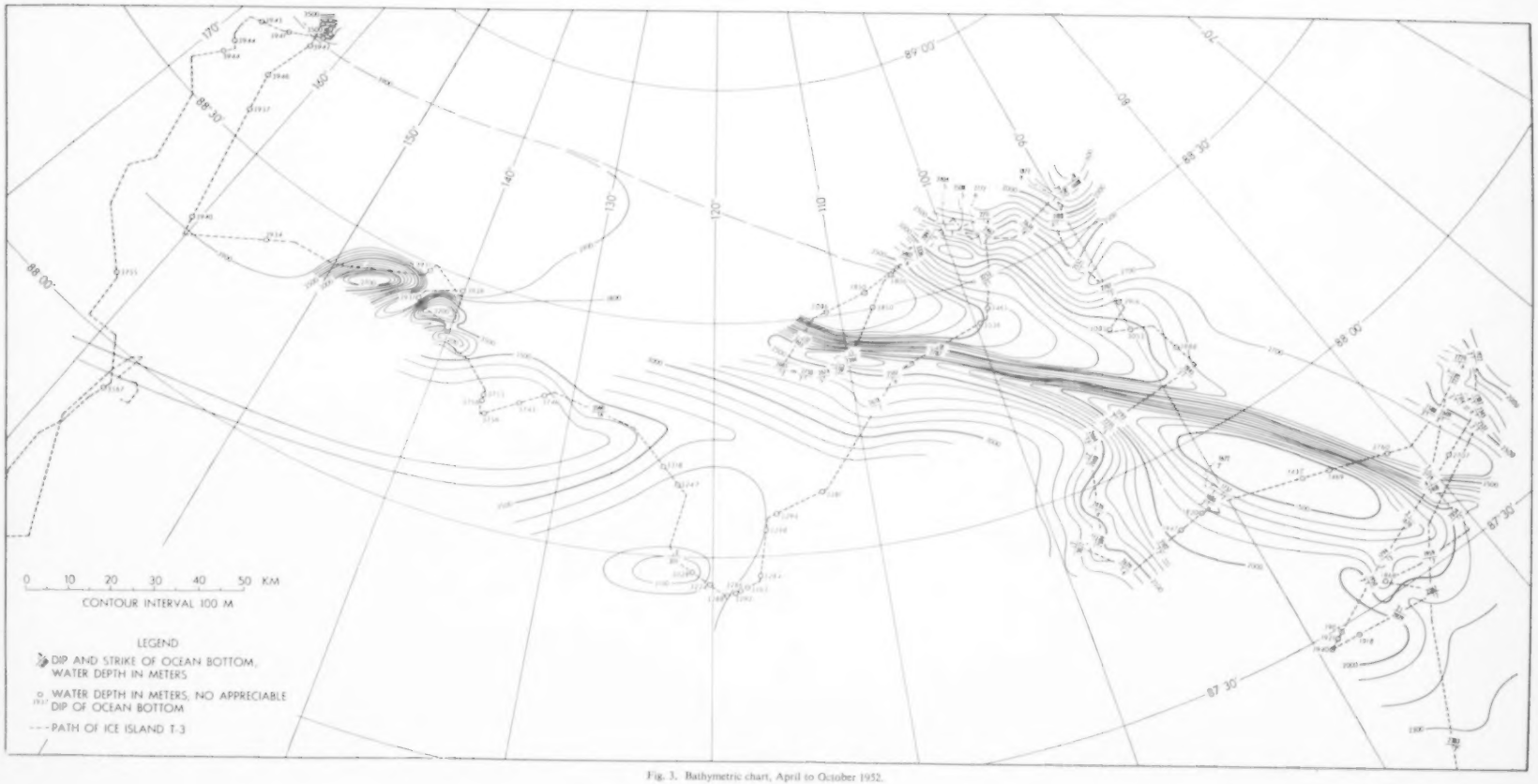
0 10 20 30 40 50 KM
CONTOUR INTERVAL 100 M
LEGEND
DIP AND STRIKE OF OCEAN BOTTOM. WATER DEPTH IN METERS
WATER DEPTH IN METERS, NO APPRECIABLE DIP OF OCEAN BOTTOM
PATH OF ICE ISLAND T-3

Fig. 3. Bathymetric chart, April to October 1952.

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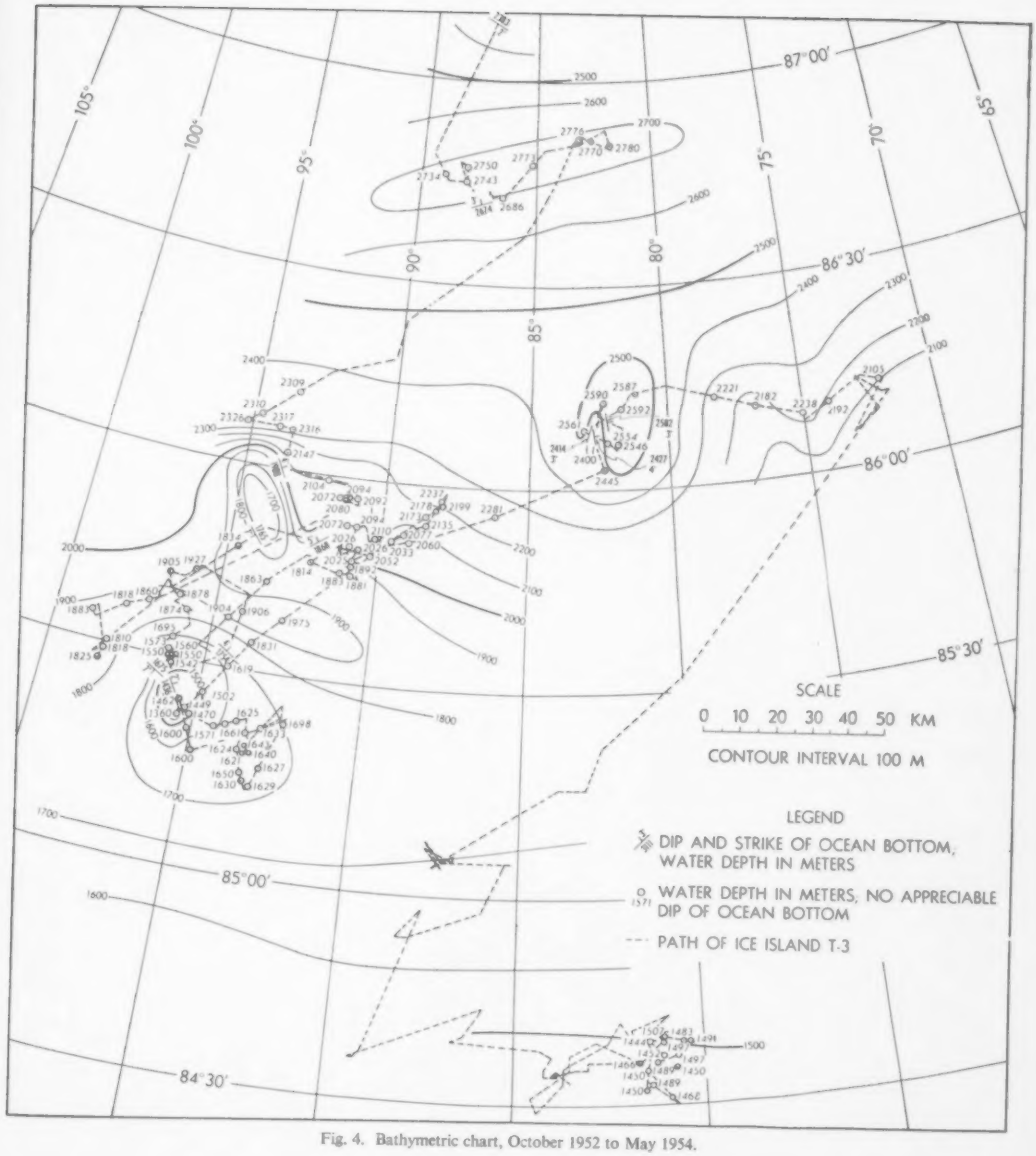

Fig. 4. Bathymetric chart, October 1952 to May 1954.

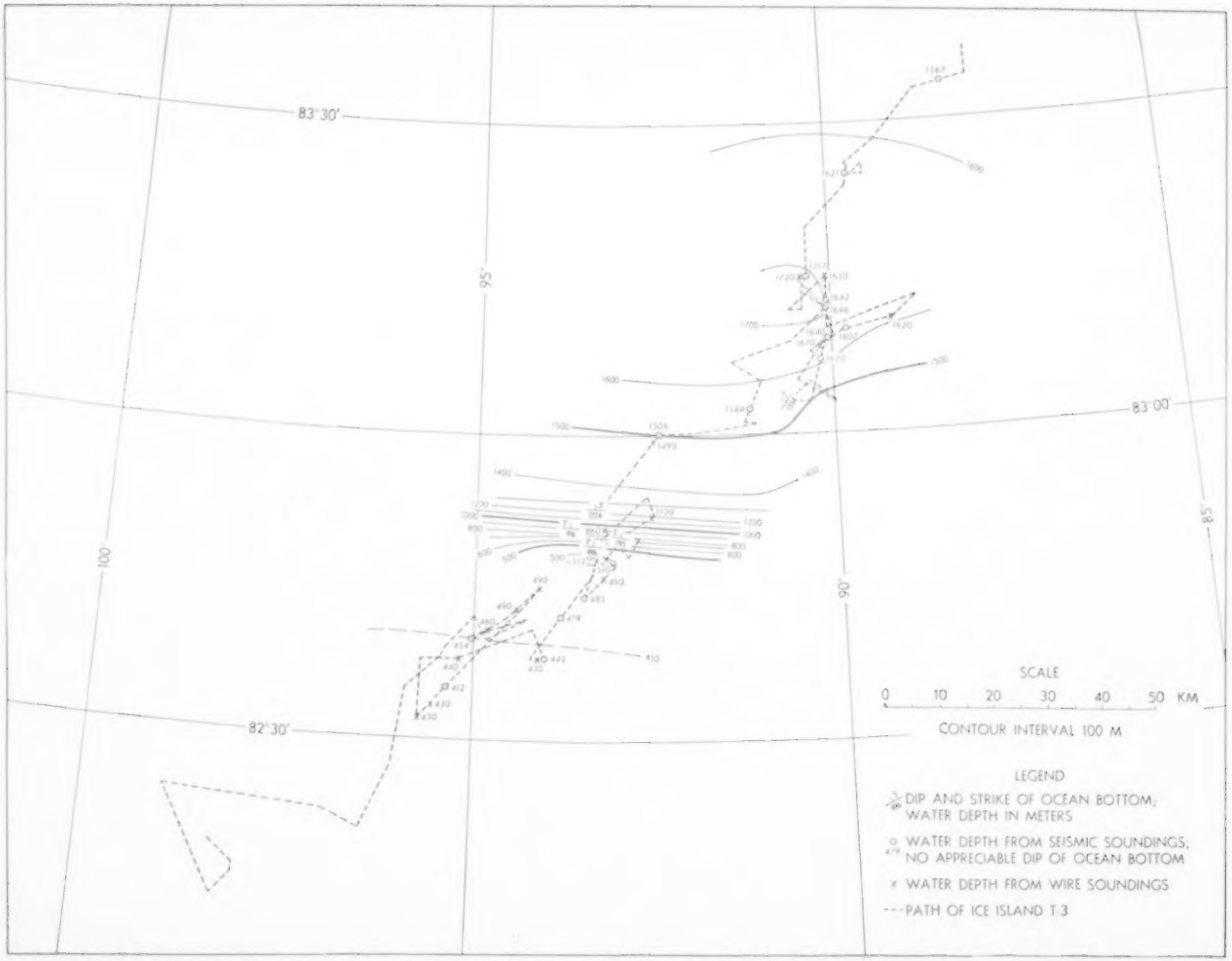

Fig. 5. Bathymetric chart, May to September 1955.

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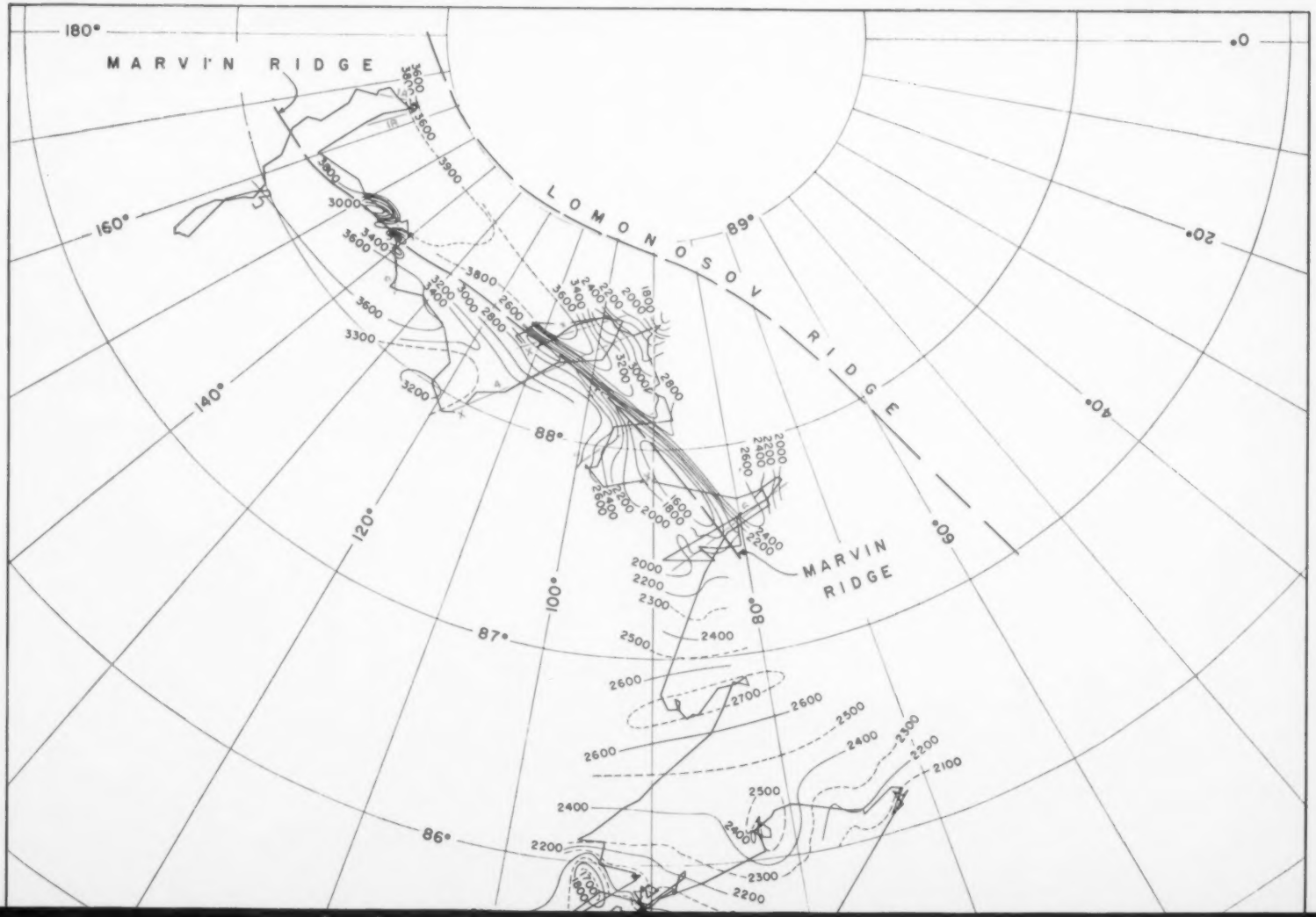
180°
MARVIN RIDGE
0°
160°
LOMONOSOV RIDGE
89°
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140°
88°
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120°
60°
MARVIN
RIDGE
100°
87°
80°
86°

MARVIN RIDGE
LOMONOSOV RIDGE
MARVIN RIDGE
180°
160°
140°
120°
100°
89°
88°
87°
86°
0°
20°
40°
60°
80°

Fig. 6. Composite bathymetric chart showing locations of sections.

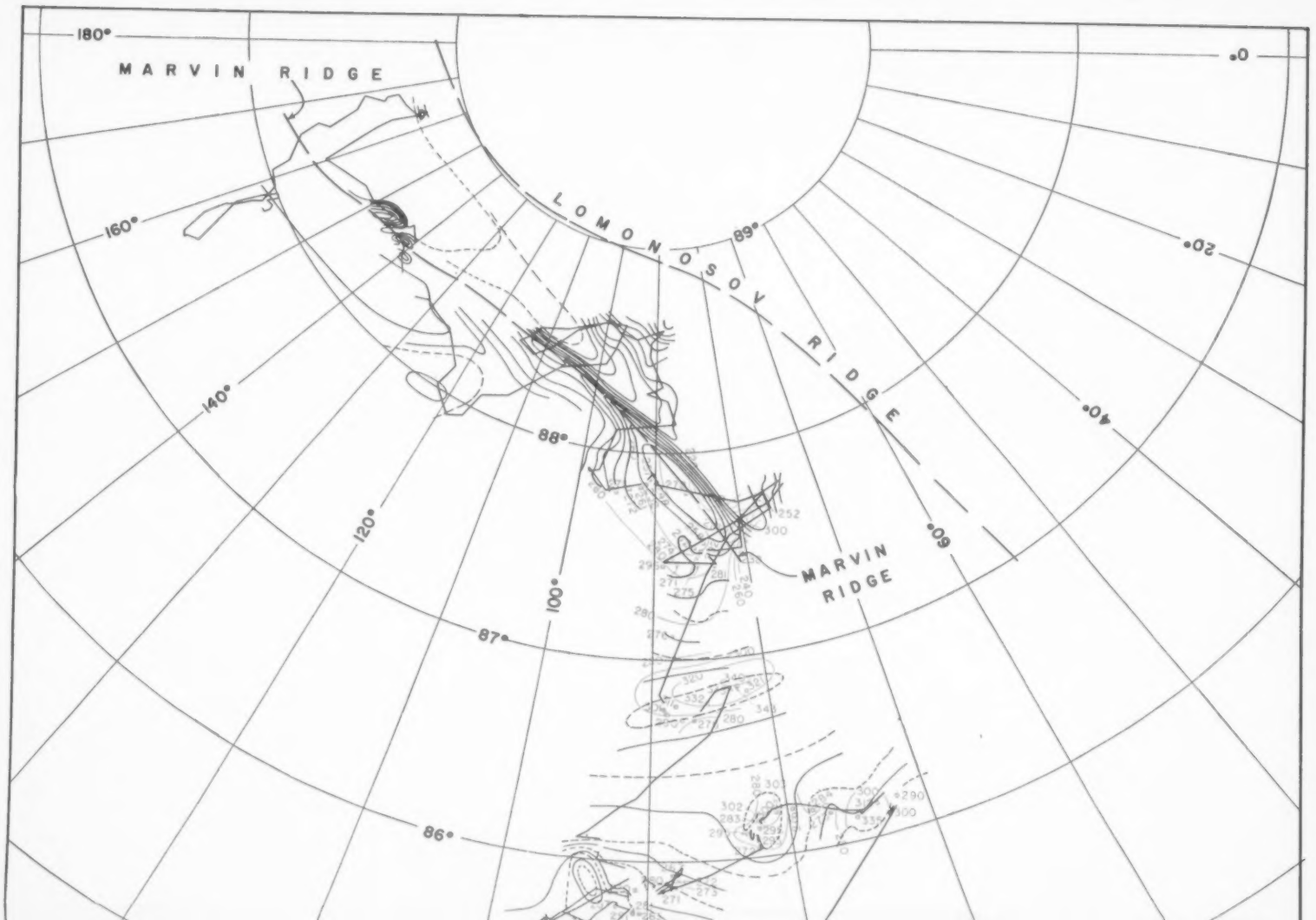
180°
MARVIN RIDGE
0°
160°
LOMONOSOV RIDGE
89°
20°
140°
88°
40°
120°
100°
60°
MARVIN RIDGE
87°
86°

Fig. 16. Lines of equal thickness of undisturbed sediment layer shown superimposed on bathymetric contours (thickness values in metres).

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depths of the valley floor. The contouring of this part of the ridge is very difficult because of the scarcity of data and somewhat uncertain locations. The records were good, however, and the strike and dip information as shown is reliable. On the southern side of the valley again beginning abruptly (at approx. 151°W), very steeply dipping reflections were obtained from a high ridge rising at least 1200 m above the valley floor. As the island moved across only the north side of this feature, nothing definite about the total height can be ascertained though subsequent depths to the east appear to limit the rise to a figure around 1200 m. The south arm of the level valley floor extending east of this feature isolates it from a similar high a few kilometres toward the east (at approx. 139°–141°W). Along these two poorly mapped highs occurred the only poor reflections obtained from the ocean bottom. These are shown with the letter " P " by the depth value. It is expected that these poor reflections are the result of lack of sufficient plane reflecting surface, rather than of changes in acoustic property of bottom material. Farther to the west the extent of the southern ridge is problematical. Although a gravity high is present (at about 165°W and just south of 88° 15′N) no depth measurements were obtained in this area.

The extent of the plain between the two ridges can best be seen in Fig. 3. A slow rise occurs toward the east of a little less than a hundred metres over approximately 140 km, which represents an average slope of only a few minutes. The relative reflection depths can be considered correct to about two meters including variations in timing reed corrections. It is noted that the variations north and south across the valley (between 140° and 170°W), though irregular, show no trend toward lower depths in the centre. The constant depths in the narrow valley arm (approx. 142°–143°W) between the two high features is quite remarkable considering the steepness of the rises. Another isolated abyssal plain is believed probable farther to the south, for the depths are constant here at nearly 3750 m and correlate with a similar single value obtained about 90 km to the west.

The area shown in the eastern half of Fig. 3 is well mapped. The escarpment, with a drop of about 1300 m, was crossed five times. The similarity of features on opposite sides, and the alignment of the steeply dipping zone is good evidence of a fault structure. General alignment with the high to the west is also good, but details of this configuration, especially of the valley arm indicate perhaps a different type of orogeny along the same zone. Along the eastern side of the escarpment in Fig. 3 weaker and poorly aligned dip information indicates a possible end to the fault structure.

In Fig. 4 the area south of this steeply dipping zone is outlined where the island drifted back and forth between the 70th and 100th meridians, gradually moving southward. From the values of about 2750 m found approximately 100 km south of the escarpment (at approx. 86° 50′N) there is a general rise to 1500 m (at approx. 84° 40′N) with irregularly located highs of possible volcanic origin. Indeed, along hardly any part of the path where depth measurements were made was the ocean bottom free of anomalies. The three highs that are mapped have at most 200 m of closure, the one in the northeast perhaps less than 100 m. This latter appears associated with a rather extensive low which nearly surrounds it. The T-3 drift early in 1954, shown in the extreme southeastern part of Fig. 4, was in an area with depths between 1450 and 1500 m but these are so variable that contouring at a smaller interval than that shown is almost impossible with the data available.

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The area traversed and depths obtained in 1955 are shown in Fig. 5. This area, not far off the northwest Ellesmere Island coast, shows in some detail the crossing of the continental slope near 82° 50′N and 93°W. Depth of the continental shelf at the top of the slope is about 500 m. The continental slope has a 3° dip that is almost due north for a drop of about 800 m following which a gentler slope is obtained to a low of over 1700 m. The east-west strike of the continental slope under the path of the island varies nearly 45° from the trend of the northwest Ellesmere coast line.

The combination of these bathymetric charts covering the area between Ellesmere Island and the North Pole is shown in Fig. 6.

SUB-BOTTOM SEISMIC STUDIES

Sections

The reflection data from below the ocean floor was not extensive either in area covered or in depth. In all instances the explosions used for seismic reflections were made near the surface, thereby limiting the sub-bottom depth studies to reflection times less than that of the first repeated reflections between the surface and the ocean bottom. This limit is about twice the depth of the water, but in most areas of deep water, much less depth than this was explored. Fig. 8 shows typical reflection records. Seven sections, Figs. 9 to 15 inclusive, have been plotted, all except the last being in the northwestern area of the drift. The location of these sections is shown in Fig. 6. The sections are drawn along the maximum dip of the ocean floor as much as possible although obviously the sections had to follow the line of island drift in most cases. Strikes and dips of the lower horizons were projected graphically to the line of section. In some areas in the extreme northwest this was quite difficult as the outline of a strongly dipping formation could not be faithfully portrayed by projection over more than a few ki ometres.

In Sections 1A and 1B (Fig. 9) some features of the high area in the extreme northwest are examined, as well as those of the abyssal plain south of this along the line of island movement. Two features are noteworthy ; the uplift reflected in lower beds of the plain at considerable distances to the south, and the abyssal plain containing many reflecting horizons that do not show good correlation or persistence across the width of the plain.

Section 2 (Fig. 10) crosses the range of hills south of the plain and extends farther south to a second flat area. The series of folded and possibly fractured ridges shows some inconsistency in the reflected dips due both to necessary projections and to possible errors in locations for some positions. Again, as in Section 1 (Fig. 9), very strong dips are noted under the flat surface of the plain. This section illustrates also the extreme flatness of the plain up to the very foot of the uplift, as though the material forming the bottom features of the plain were subject to laws of movement not unlike those of a fluid material.

Sections 3, 4, 5 and 6 (Figs. 11-14) cross the main part of the Marvin Ridge and extend north to the southern flank of the Lomonosov Ridge. In general the beds seem conformable though there is some evidence in Section 3 (Fig. 11) of flat beds in the valley floor over dipping structures. The fault terminating the Marvin Ridge on the north had much less dip on Section 6 (Fig. 14). In the south part of Section 6 is noted the very good, persistent second reflection which will be discussed in more detail below.

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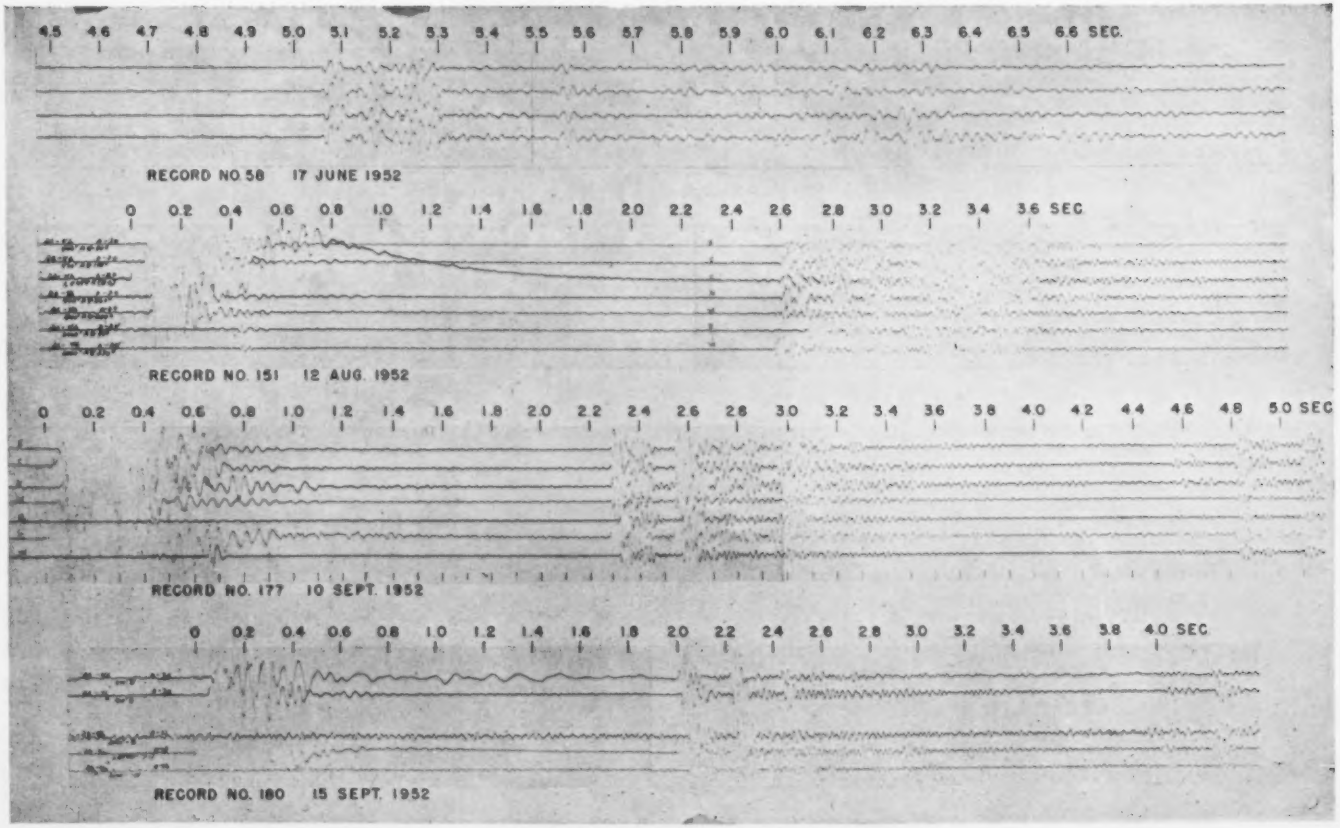

Fig. 8. Typical seismic reflection records.

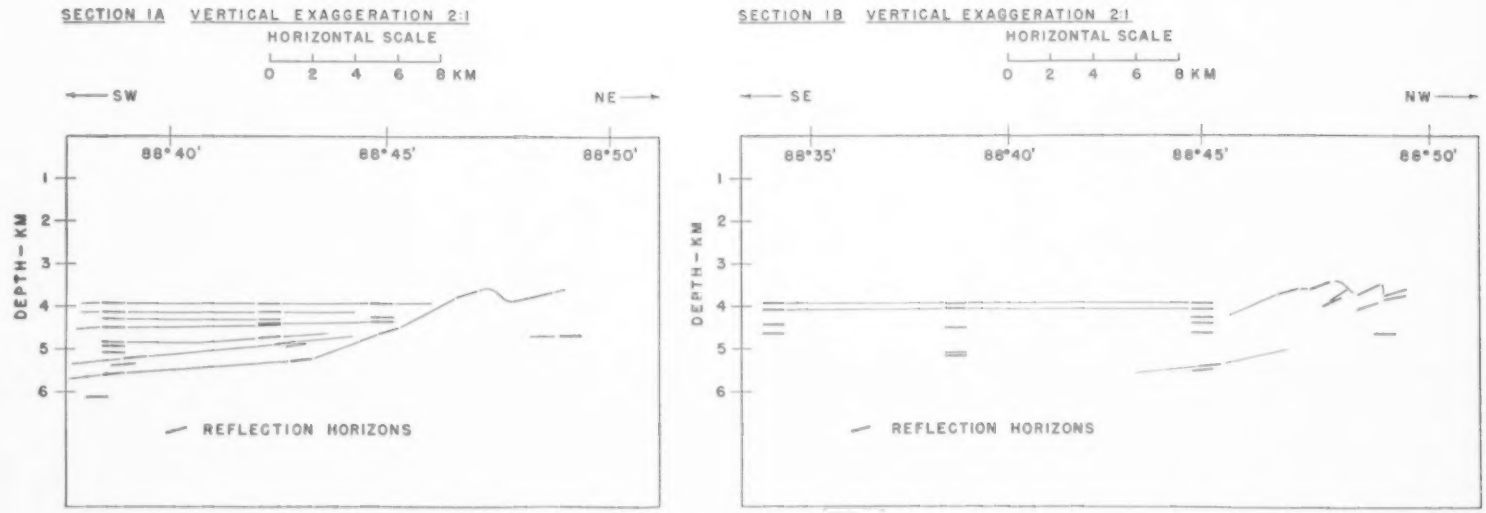

Fig. 9. Section 1a, 1b.

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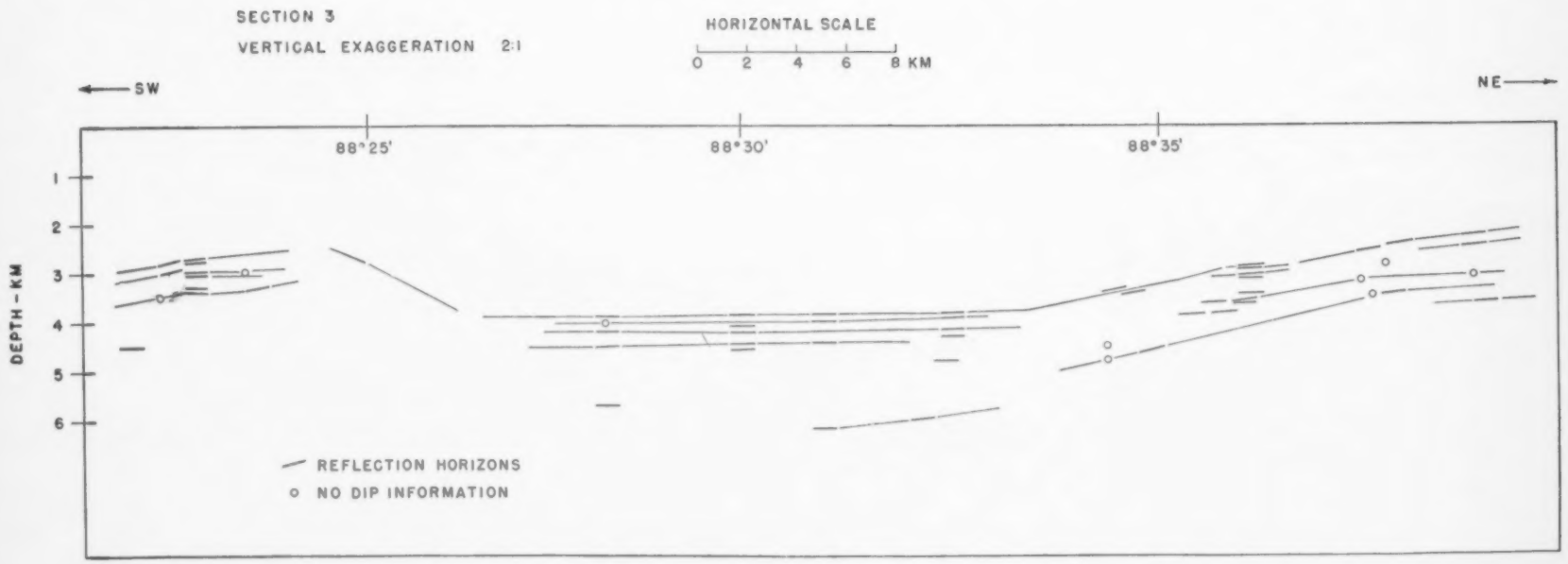

Fig. 11. Section 3.

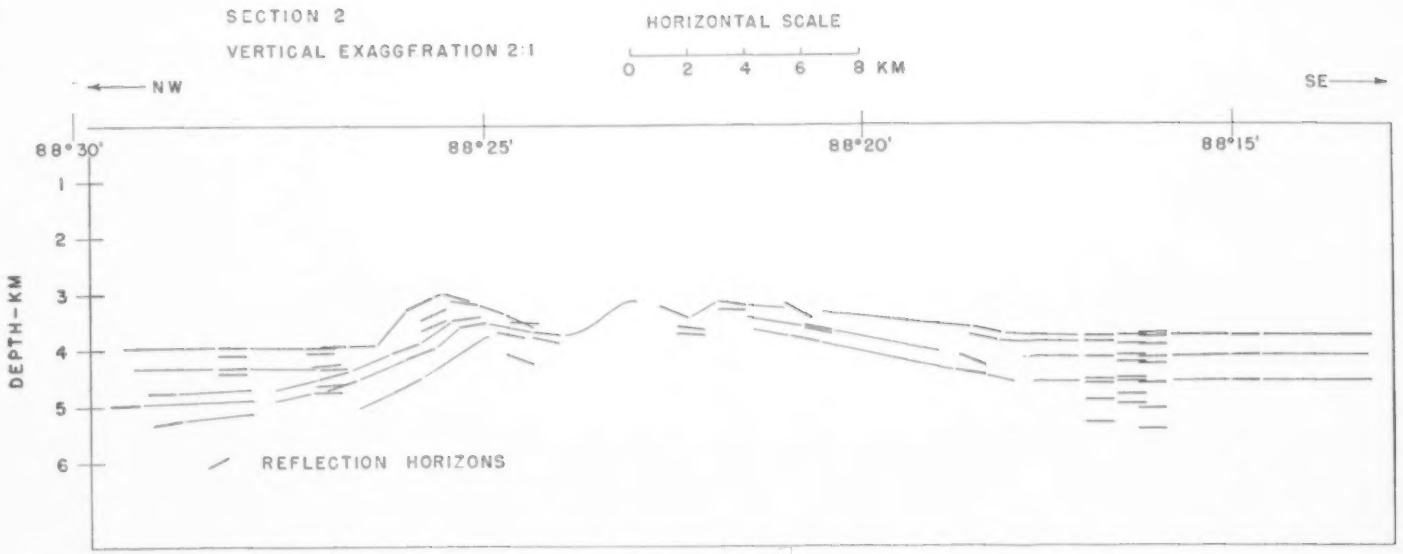

Fig. 10. Section 2.

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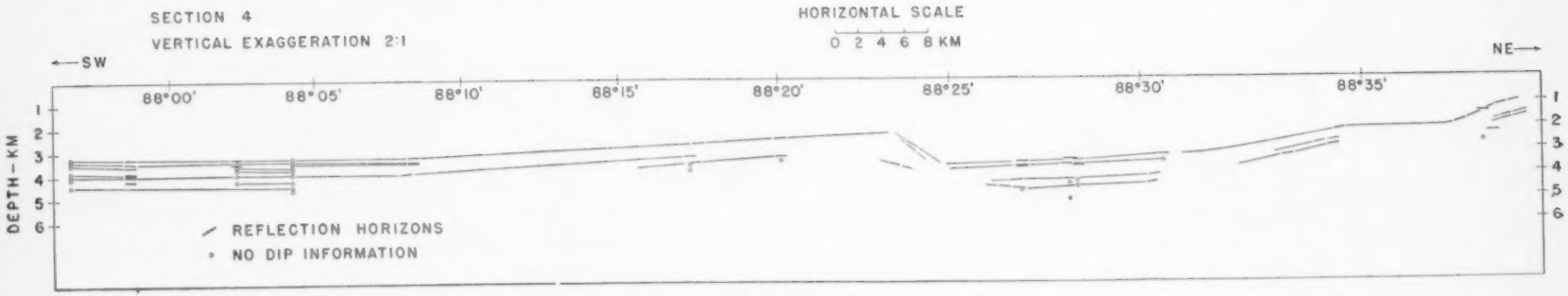

Fig. 12. Section 4.

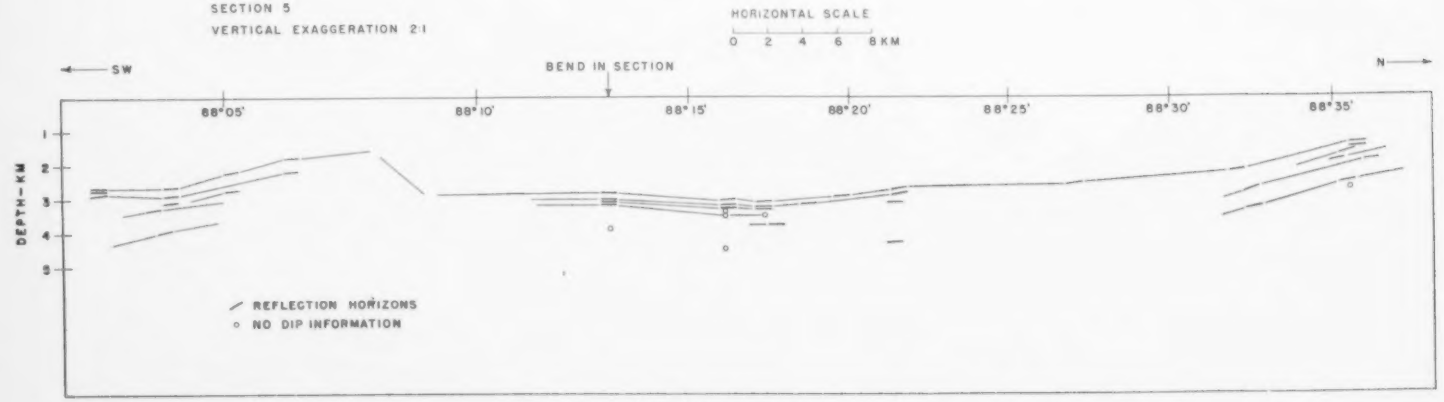

Fig. 13. Section 5.

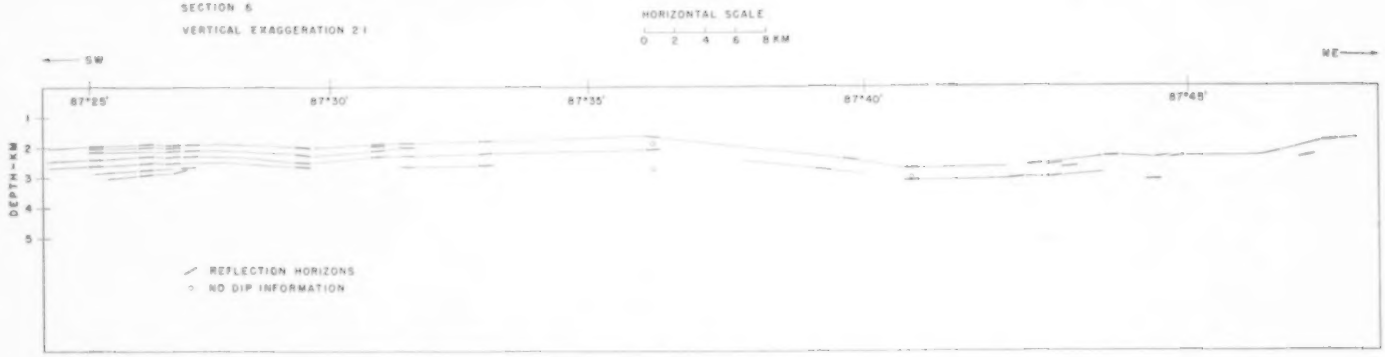

Fig. 14. Section 6.

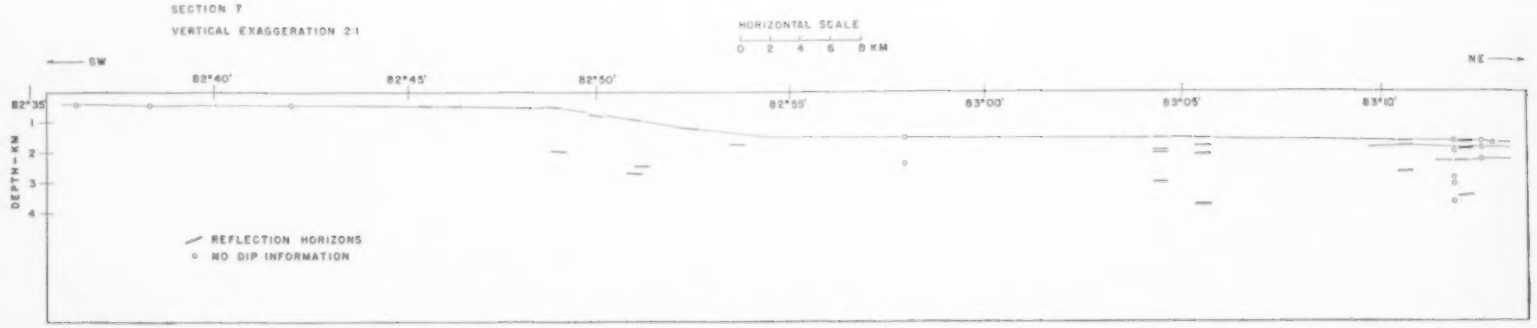

Fig. 15. Section 7.

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Section 7 (Fig. 15) shows the details of the continental slope off northwestern Ellesmere Island. Sub-bottom reflections are not good though it is noted that a few under the continental slope have less dip than the surface reflections.

Second reflection

Throughout the eastern part of the explored region, beginning abruptly on the western slope of the Marvin Ridge near 87° 50′N and 95°W, a second reflection of extremely good amplitude preceded by an unusual low-return reflection zone is present. Typical second reflections are illustrated in Records 177 and 180, Fig. 8. This type of reflection is unique to ocean areas and has been discussed by HERSEY and EWING (1949) for large expanses of the Atlantic Ocean. Similar seismic records made by WIEBULL on the *Albatross* expedition have been interpreted as representing total depth of ocean sediment (PETTERSON, 1954). The study by HERSEY and EWING showed that this type of reflection, which they termed M-type, occurred in an area of relatively smooth ocean bottom with the interval varying between 0·05 and 0·63 seconds. Where the strong second reflections in the Arctic area were present the water depths varied from 1400 to 2800 m, and the time interval from 0·21 to 0·34 sec although 75 per cent of the values fall between 0·25 and 0·30 sec.

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There are several interesting questions in regard to this second reflection. What does this represent? Why is it limited in areal extent? What is the significance of the variation in time intervals? There can be no completely satisfactory answer to these questions without a great deal of further information. We may say, however, that a strong second reflection comparable to the bottom reflection signifies generally that there is an acoustic contrast between layers similar to that found at the ocean bottom. This does not necessarily imply that this lower layer consists of solid rock. Results of refraction tests discussed later do not indicate a particularly high velocity discontinuity. Underwater volcanic eruptions may introduce a high velocity contrast, but such eruptions could not explain the wide area distribution noted here. It is believed that the significance lies less in the amplitude of the second reflection than in the extreme quiet zone preceding it. Such a uniform quiet zone could only be attributed to a sedimentation undisturbed by variations in climate, volcanic activity, or by turbidity currents. Unfortunately the records are not adaptable to a detailed study of the thickness of the zone of undisturbed sedimentation, but a correlation of reflection events between records of extreme interval limits shows that the undisturbed zone remains fairly constant in thickness and that the time differences from one record to another may be accounted for by a non-uniform cover of more recent origin. This top cover represents approximately one third to one half the total interval. Fig. 16 shows the extent of the area in which this second reflection with the associated quiet zone was obtained though this are is not defined to the east and south. It perhaps can be assumed that in this zone and in this zone only, of the total area explored, sediments were continually deposited without interruption. The thickness of the quiet zone is roughly 250 to 300 m. If the estimate of rate of deposition in the deep Arctic of one centimetre per thousand years by EWING and DONN (1956), and by SAKS, BELOV, and LAPINA (1955) is representative, this quiet zone can represent sediments accumulated 15 to 30 million years ago, starting in the Tertiary Period. The sudden beginning and cessation of this uniform deposition over such a large area was most likely brought about by drastic climatic changes. To attribute this

layer to the entire non-glacial period between the Permian and Quaternary would require deposition rates considerably smaller than estimated above, but it seems much too thick to represent a deposition of the Quaternary interglacial period alone.

The limit in the extent of this quiet zone can perhaps best be explained by pointing out conditions unfavourable to such a sediment accumulation in some of the other places examined. In the northwest in the areas of the extremely flat valley and the high Lomonosov and Marvin Ridges turbidity currents could well have played an important part in preventing the deposition even though this area is not seismically as active as the comparable mid-Atlantic Ridge. Farther south and west of the 90° meridian, which generally marks the limit of the zone of the quiet interval, two prominent peaks dominate the area. These may well be volcanic in origin. Second reflections here are very limited and variable. The reflections obtained in 1954 near 84° 30′N and 82°W all show the quiet zone although this area is only about 175 km north of the Ellesmere shore. In 1955 when seismic recordings were made at distances of only 100-130 km from land, no evidence of the quiet zone was found.

Fig. 16 shows the variation in the thickness of this zone. The velocity in these upper sediments, as discussed below, is very close to 2·0 km/sec within the limit of accuracy of determination. Hence the interval in seconds is identical to the thickness in kilometres. Although the thickness of the sediment layer increases in the bottom of the broad syncline near 86° 45′N, and the smallest values fall in the shallower area in the southeast, this relationship seems local rather than widespread. In the high area near 87° 50′N and 87°W there is a very striking minimum thickness on the western side where the dip is steepest even though here the maximum dip value is little more than 2°. The reflections obtained preceding the quiet interval make it appear that the difference is in the duration of the quiet zone. Directly on the high, thickness values become greater. Then at the very edge of the fault zone extreme low values are noted where the shallow reflections are missing, indicating loss after the uninterrupted depositional period. The two isolated low values of 252 m on the downside of the fault are difficult to explain. Going south through the broad syncline, the thickness becomes maximum although dip is very low, generally less than 1°. Still further south on the summit of the small high at 86° 10′N and 84°W, there are no characteristic second reflections and thicknesses of the quiet interval in the immediate neighbourhood around this high are greater than average. This high is probably a small volcano which has become active following the depositional period and has deposited an average of 30 to 40 m of material over the surrounding area.

Seismic velocity studies

Seismic velocity of sediments above second reflection. The quiet zone preceding the strong second reflection made it possible to obtain times to the beginning of this reflection as accurately as to the reflection from the ocean bottom. From the time this second reflection started appearing in August 1952 until late in October when the winter conditions made it impossible to keep close attention to equipment, two detectors were located 610 m (2000 ft) on either side of the shot point and in line with the centre geophone at the shot point. During this time seventeen records with second reflections were obtained. Of these, fourteen were usable for the determination of the seismic velocity of the interval between the sea bottom and the second reflection horizon. By means of the increased reflection time to the distant

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geophones the average velocity, $\bar{V}$, to the second horizon, was obtained from the formula :

$$\bar{V}^2 = \frac{2X^2}{T_1^2 + T_2^2 - 2T_0^2}$$

where X equals 610 m, T_0 is the reflection time of the second reflection to the center geophone, T_1 and T_2 are the times to the outlying geophones. Because of the long distances the differences in time between center and outer geophones average about 0·030 sec with an accuracy of about 0·001 sec. The assumptions in this formula are that the ray paths are straight and that the dip is uniform across the reflecting surfaces. Using this average velocity and the travel time T_0, an approximate distance to the second horizon was computed. Since the ocean depth, or distance to the first reflection horizon could be computed from knowledge of average wave velocity in water, the approximate thickness of the quiet interval was now known and the interval velocity could be obtained. Table 1 lists the pertinent data and resulting thicknesses and velocities. It will be noted that the sediment layer is approximately 250-300 m thick. An average of the fourteen interval velocities gives a value of 2·04 km/sec for this layer.

Table 1. *Seismic velocity of sediments above second reflection horizon*

Record No.	*Second reflection*		*Depth to first reflection (km)*	*Interval thickness (km)*	*Interval time (sec)*	*Interval velocity (km/sec)*
	$\bar{V}$ *(km/sec)*	T_0 *(sec)*				
172	1·518	3·147	2·102	0·287	0·1355	2·117
173	1·474	2·937	1·947	0·218	0·136	1·603
174	1·484	2·754	1·820	0·223	0·1305	1·708
175	1·524	2·565	1·686	0·269	0·126	2·135
177	1·505	2·551	1·672	0·248	0·1285	1·930
178	1·506	2·629	1·737	0·243	0·124	1·960
179	1·468	2·249	1·435	0·216	0·139	1·553
190	1·573	2·717	1·794	0·345	0·129	2·675
192	1·557	2·882	1·904	0·340	0·137	2·482
193	1·521	2·910	1·921	0·292	0·140	2·086
194	1·496	2·952	1·940	0·268	0·148	1·811
195	1·510	2·897	1·918	0·269	0·1355	1·985
197	1·543	3·108	2·067	0·331	0·1405	2·355
200	1·531	2·974	1·959	0·318	0·146	2·179
				Average interval velocity		2·04

Refraction profile No. 1. During early July 1952 near 87° 55′N and 118°W a refraction survey was started, moving the shot location along the edge of the island away from the instruments. Four shots were made to distances of about 6·7 km before the summer melt streams prevented further travel along the island edge. No bottom refractions had been obtained up to that distance. Over this area the water depth, 3290 m, was extremely constant as noted in Fig. 3. This area lies south of the main ridge feature of the area.

Although no refractions were obtained, reflections were recorded at the first three distances which made possible the determination of sediment velocity from time differentials. To determine the velocity, a formula was used which compared the overall velocity to the lower reflection horizons directly with the average velocity to the ocean bottom, or,

$$\frac{\bar{V}_2^2}{\bar{V}_1^2} = \frac{T_{1a}^2 - T_{1b}^2}{T_{2a}^2 - T_{2b}^2}$$

Where $\bar{V}_1$ and $\bar{V}_2$ are the average velocities to the ocean bottom and the lower reflection horizon respectively, and T represents reflection time with subscripts designating reflection horizons 1 and 2 and detectors a and b which were approximately 310 m apart. This formula assumes that there are no slopes of the horizon and this assumption is verified by the standard reflection shots made in that area, shown on Section 4 in Fig. 12. In calculating the velocity of the water wave the curved ray-path was taken into account although the effect of curvature was quite small. After the average velocities to the various lower horizons were determined, corrections were made to obtain vertical travel times to each layer. Vertical distances were then calculated and are plotted against vertical time in Fig. 17. The slope of the line through these

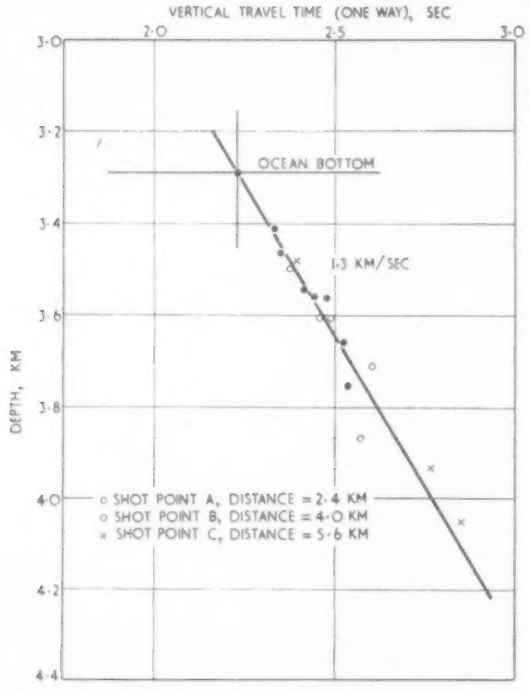


Fig. 17. Vertical travel time vs. depth at 85° 55′N, 118°W.

points gives the value of sediment velocity. For about 0·8 km below the bottom the slope indicates a velocity of about 1·3 km per second, which is lower than water velocity by about 15 per cent.

Refraction profile No. 2. A second refraction attempt was made 1 August 1952 at 88° 22′N 111°W at a site very close to the top of the ridge immediately north of the area described above. Fig. 18 shows the location of the shot relative to the equipment and gives the bathymetric information available. Only a single shot was made, this at the most remote part of the island from the instrument setup, a surveyed distance of 12·1 km. Two low frequency detectors were set out for this

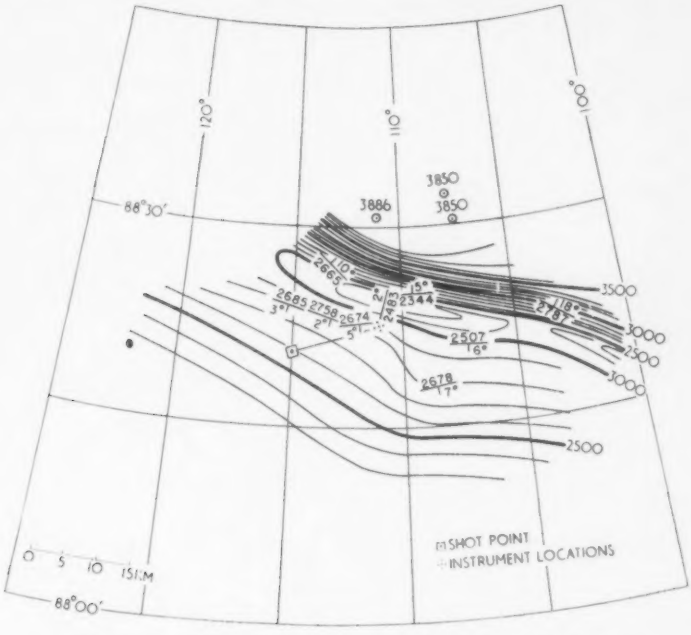


Fig. 18. Location and orientation of refraction profile No. 2.

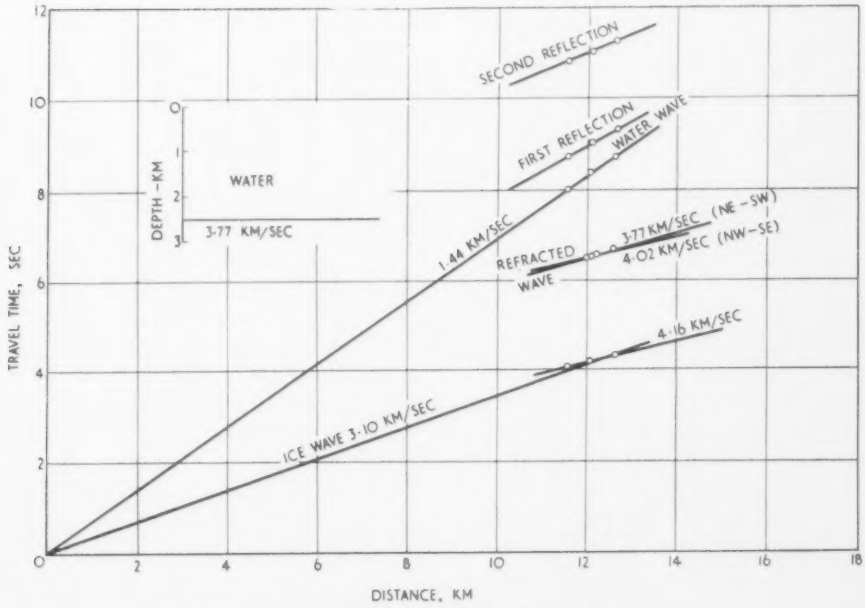


Fig. 19. Time-distance curve, refraction profile No. 2.

shot at distances of 610 m from the center of the normal reflection spread. No time breaks were available due to malfunction of the radio equipment. The reduction of the data was done by the identification of the water wave, the single and double reflected waves from the bottom, and the refractive wave. An additional wave was recorded but was unidentified except that it was probably associated with the ice island which was between the shot and the recorder over part of the distance. Fig. 19 shows the associated time-distance curve. The velocity of the refracted wave was determined from velocities along the two lines of instruments at right angles to each other. Since the velocity associated with a line of geophones represents the velocity along that line, and as dip information was available beneath the instrument spread from a reflection shot fired just after the refraction, the true velocities associated with the refracting layers can be calculated. Along the northwest-southeast line of instru-

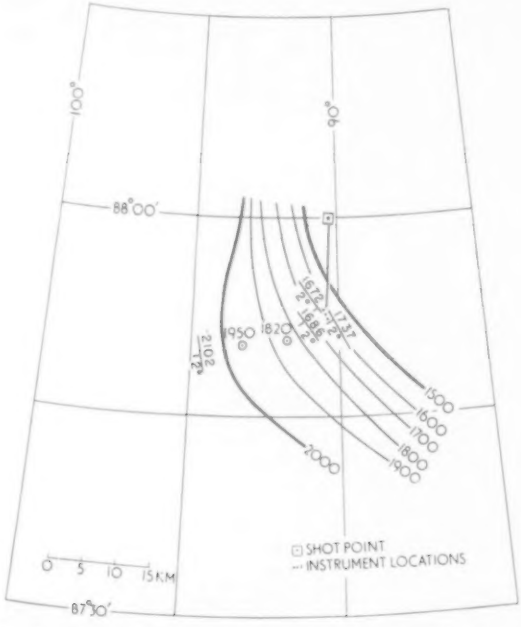


Fig. 20. Location and orientation of refraction profile No. 3.

ments where the slope was 1·4° toward the shot, the velocity was 4·02 km/sec. Along the northeast-southwest line of instruments with slope of 0·8° toward the shot, velocity was 3·87 km/sec. True velocity of the refracting layer corrected for dip is 3·77 km/sec. From approximate depths as shown in Fig. 18, the depths at reflecting points were estimated and from these the average water velocity including corrections for curved ray-path was obtained. With this average water velocity, the known times of first and second reflections, and the depth under the instruments, the average dip between shot point and recorder was determined. For the first reflection this was 2·8° and for the second 2·2°. These are in general accord with the dips as shown in Fig. 18.

A refraction wave from the bottom with this known average dip, depth and velocity gives a theoretical travel time of 6·66 seconds as compared with 6·58 actually obtained. This discrepancy of 0·08 seconds, comparable to about 60 m, could be accounted

for in small errors in dips or velocity. It is significant that little or no low-velocity material is present on the relatively steep slope of the ridge.

Refraction profile No. 3. The third refraction attempt was made 10 September, 1952 at 87° 53′N and 91°W in 1670 m of water. The setup was approximately the same as on the previous shot and again radio breaks were not obtained, therefore, times were found by use of known distances and identification of the water waves. Fig. 20 shows a map of the area and bathymetric results available. The refraction profile was on the ridge area where the second reflection was very good. The line between the shot point and recorder was nearly along the strike of the bed.

The refraction velocities obtained were the true velocities as there were no dips shown along the line of geophones on reflection shots. Reflection data, however, show about 0·5° of dip up to the shot point. The value of dip agrees closely with that

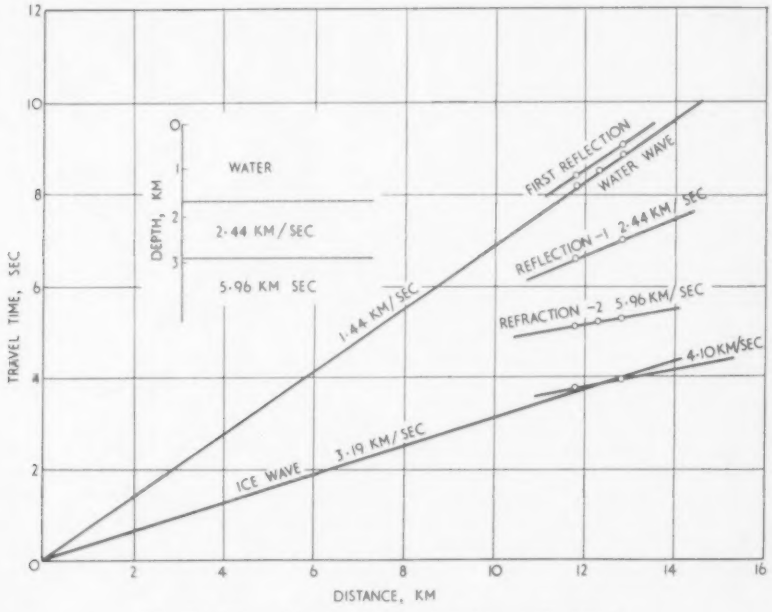
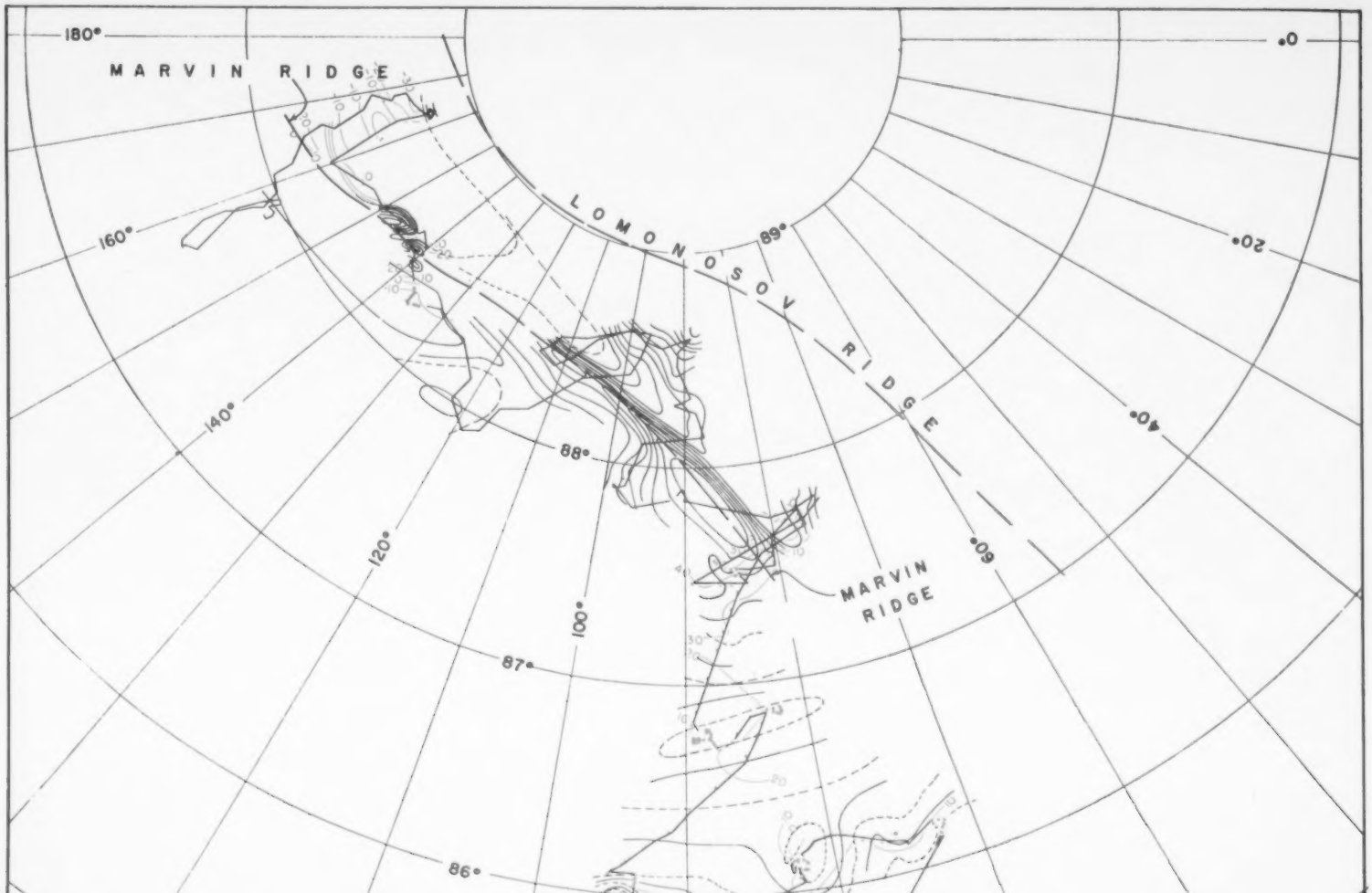


Fig. 21. Time-distance curve, refraction profile No. 3.

indicated by the contours. Fig. 21 shows the associated time-distance curves. A velocity of 2·44 km/sec was obtained for the bottom sediments which is comparable to the 2·04 obtained above with the reflection method. The higher refraction velocity, 5·96 km/sec, is at a depth of about 1320 m below the bottom but this cannot be relied upon too much as there were no good reflecting horizons at that depth from which a dip could be obtained. However, nearby reflection shots, while showing no marked reflection at that depth, do not show abnormal dip. This depth is definitely well below the horizon of the second reflection, which was found previously to have unusually high amplitude and for which no refraction wave was noted. The ice wave is also noted in this refraction shot at almost identical time and velocity to the wave obtained in the previous refraction shot where ocean depth was considerably different.

Fig. 23. Contours of free-air gravity anomaly superimposed on bathymetric chart (anomaly values in milligal).


180°
MARVIN RIDGE
0°
160°
LOMONOSOV RIDGE
89°
20°
140°
88°
40°
120°
60°
MARVIN RIDGE
100°
87°
86°

Refraction profile No. 4. In the summer of 1955, while the island was at the edge of the continental shelf, in a water depth of 512 m a refraction shot was made at a distance of about 3·5 km from the standard reflection spread. A refracted wave was received followed in 0·465 sec by the water wave. From the configuration of the geophone spread and the direction toward the shot point a velocity of 2·3 km/sec was found. The dip of the ocean bed was about 1·5° towards the north, but the line of geophones and the line between the instruments and shot point was as nearly along the strike as the accuracy of the latter could be determined To the extent that the bottom dip is known the 2·3 km/sec velocity was that of the ocean floor or within a few tens of metres below the floor.

GRAVITY STUDIES

Observations and gravity anomalies

Approximately 350 gravity values were obtained during the period April 1952 to May 1954 at the ice island with the North American gravimeter. Although physically imperceptible, the amount of vertical motion is considerable greater than on land areas. The gravimeter, acting as a seismograph with a natural period of about 18 seconds, was sensitive to the long period vertical motions, but in nearly all cases the motion of the cross-hair across the reading scale was within the limits of the instrument stops. Observations were made by setting the meter dial at a position that would keep the cross-hair on scale, then reading its position every five seconds for a six minute period. These values were then averaged and reduced to a common scale-value from known instrument constants. Fig. 22 shows typical cross-hair movements for two differing conditions.

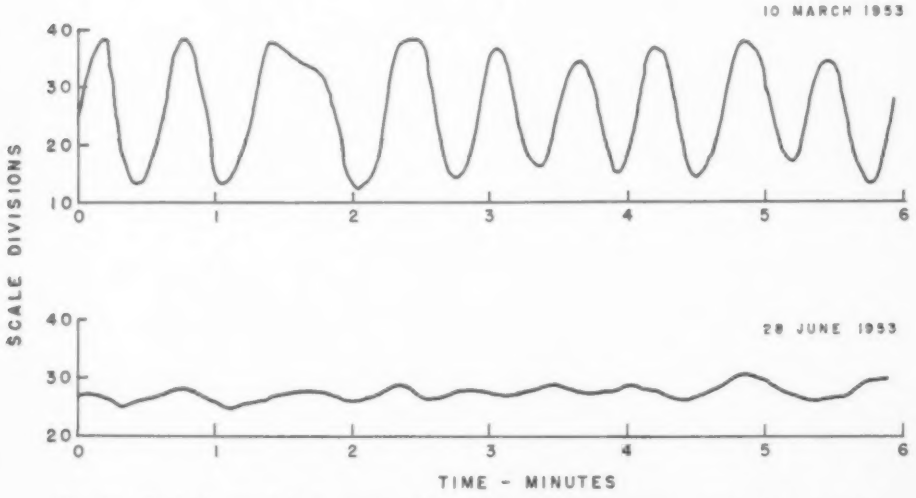


Fig. 22. Typical cross-hair movement, North American gravity meter on ice-island, T-3.

Gravity values for the various locations of the island were obtained by determining the differences from the station at Thule, Greenland. The gravity value at Thule is taken as 982.9280 as given by WOOLLARD, BLACK, and BONINI (1954). The meter

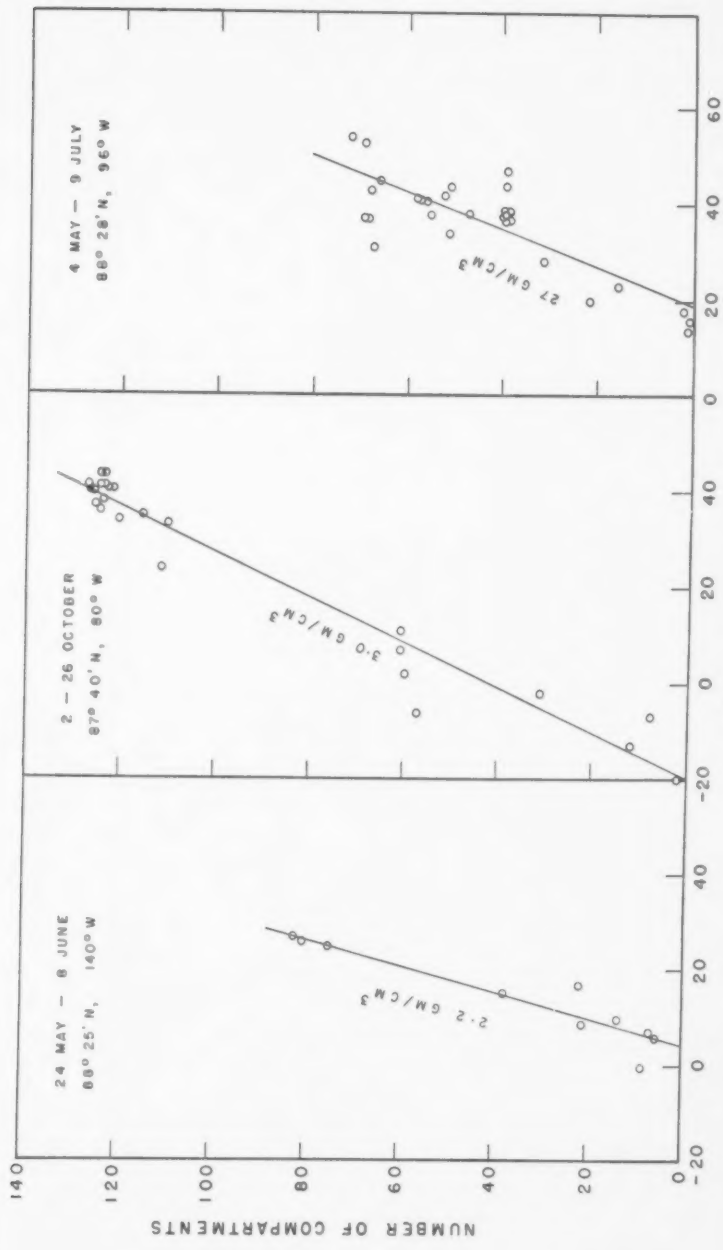


Fig. 24. Number of effective gravity compartments vs. free-air anomalies.

was essentially drift free as indicated by the following misclosures between readings at THULE before and after operations on the ice island :

Leave Thule April 1952, return June 1953 : Misclosure 1·2 milligal.

Leave Thule October 1952, return January 1953 : Misclosure 6·6 milligal.

Leave Thule March 1953, return October 1953 : Misclosure 3·1 milligal.

Leave Thule March 1954, return May 1954 : Misclosure 1·1 milligal.

Both the value of gravity at Thule and the instrument constant at high latitudes need further confirmation.

The free-air anomalies were obtained from the observed gravity values as compared with values computed from the International Gravity Formula. A contour map of these anomalies superimposed over the bathymetric contours is shown in Fig. 23. In the higher latitude areas, where there is considerable bottom relief, the anomalies ranging from + 40 to − 30 milligal are dependent on the water depths, which vary from 1450 to 3950 m. In the areas south of about 87° North Latitude, where the relief was less, the anomalies were mostly positive with the maximum being + 54 milligal over an area of shallow water.

Density calculations

The free-air anomalies measured during crossings of the Marvin Ridge and during the drift of the island near the high area at 85° 28′N and 96°W were used in an attempt to compute the average densities of these features. In order to calculate the theoretical

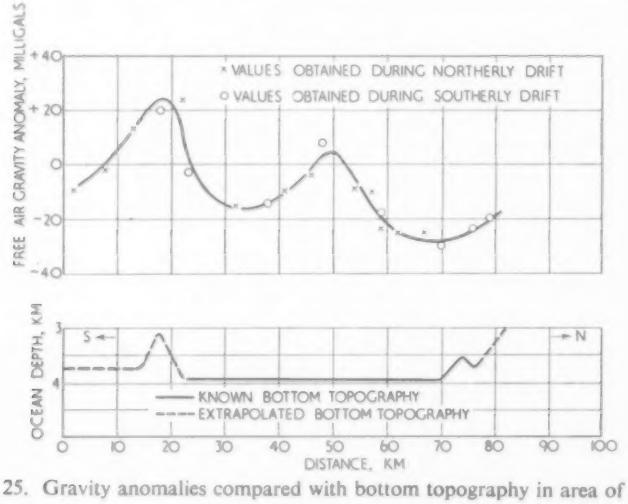


Fig. 25. Gravity anomalies compared with bottom topography in area of level valley.

gravity effect of the sea bottom irregularities, horizontal templates with 72 compartments were constructed for each 400 m thickness in such a way that each compartment would represent an equal vertical gravity effect at the station for an infinitely extended structure. For each observed gravity station the number of compartments in which the bottom structure appeared for pertinent 400 meter levels was counted. Fig. 24

shows the relation between the number of such compartments and the observed free-air gravity anomalies in the three areas under consideration. From least-square determinations of the slope of these lines, the densities determined were as follows :

88° 25′N	140°W	2·2 g/cm^3
87 40	80	3·0
88 28	96	2·7

The scattering of points for each of the areas is evidence of the lack of sufficient depth data for an accurate portrayal of the bottom. The densities cannot therefore be considered too reliable.

Above the level valley in the far northwestern part of the island route, a gravity high was noted on each of the two crossings. Fig. 25 shows the gravity anomalies across this area, the high values presumably signifying a deep-seated feature.

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Air Force Cambridge Research Center

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The beryllium-10 concentration in deep-sea sediments

P. S. GOEL, D. P. KHARKAR, D. LAL, N. NARSAPPAYA, B. PETERS, and V. YATIRAJAM*

Abstract—The cosmic-ray-produced radioactive isotope, ^{10}Be (half-life 2·7 million years) has been discovered in the upper and lower portions of a 15 m long core from the sediment of the Pacific Ocean. A comparatively simple chemical procedure for its extraction has been developed.

If the investigated core represents sedimentation which has remained physically and chemically undisturbed for several million years, the following tentative conclusions can be drawn : The measured concentrations of ^{10}Be in layers at various depth indicate a sedimentation rate of about 5 mm/1,000 years which is not far from current estimates.

The concentration in the upper layers leads to a present-day deposition rate of $2{\cdot}55 \times 10^{10}$ ^{10}Be nuclei/cm^2 year, in excellent agreement with estimates based on the ^{7}Be contents of rainwater.

The decrease of concentration with depth indicates an intensity of cosmic rays in the past which has changed not at all or very slowly during the last ca. 2·5 million years.

INTRODUCTION

THE production of the long lived radioactive beryllium isotope, ^{10}Be by cosmic radiation, and its possible usefulness for geological age determinations and for measuring cosmic ray intensity of the past has recently been discussed by one of us (PETERS, 1955, 1957). In this paper, we describe experiments, which led to the discovery of ^{10}Be activity at various depths in clay sediments of the Eastern Pacific. A simple method for extracting the activity has been developed, which lends itself to routine analyses. The method is based on the fact that cosmic-ray-produced beryllium, which reaches the ocean surface as a constituent of rain water, is apparently only adsorbed on the surface of the clay particles, so that substantial fractions can be removed by a simple extraction by leaching with hydrochloric acid, and the very laborious process of a complete dissolution and fusion of the sediment is thereby avoided.

The ^{10}Be activity is identified by absorption measurements on its β-radiation and by the fact that it persists after two different chemical purification procedures both of which are specific for beryllium.

An apparently significant decrease of ^{10}Be activity with depth was observed in a 15 m long core, which was raised by the Swedish *Albatross* expedition in the Eastern Pacific (04° 04′S, 152° 53′W at a depth of 5200 m). This gives reasons for hope that certain regions of the ocean floor may have remained undisturbed for periods long compared to the 2·7 million year half-life of ^{10}Be and that therefore carefully selected samples may permit age determination of sediments and measurements of the past cosmic-ray intensity. The presence of ^{10}Be in ocean sediments has also recently been reported by ARNOLD (1956) ; his results, which are as yet confined to the upper layers of sediments, and refer to a different geographic location, are consistent with ours.

Relations, which obtain between ^{10}Be concentration in undisturbed cores on the one hand and sedimentation rates and past cosmic-ray intensities on the other,

*Present address : National Chemical Laboratory, Poona, India.

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have already been discussed by PETERS (1957). Applications of the results obtained so far show that the measurements are consistent with the activity which one must expect on the basis of deposition of ^{10}Be nuclei from the atmosphere as it exists today and that the mean sedimentation rates are reasonably close to the current estimates of oceanographers. They indicate a constant or very slowly varying intensity of cosmic radiation for $1\frac{1}{2}$-3 million years, a conclusion which can, however, only be verified after results from different parts of the ocean can be compared.

EXPERIMENTAL DETAILS

Sediment cores

The cores, which we have investigated, were obtained by the Swedish *Albatross* expedition 1947-1948 from the Pacific ocean at a mean depth of 5200 m at 04° 04'S and 152° 53'W. The cylindrical core of diameter 4·6 cm, and length 15 m was divided in two halves along its length. Four sections of one-half of the core were analysed. The details are summarized in Table 1.

Table 1

Core section	*Depth below the ocean floor (cm)*	*Remarks*	*Total length (cm)*	*Weight of the dry core, g*	*Density, g/cc*
A	132-169	—	37·0	73·0	0·238
B	1401·5-1449·0	11 cm removed	36·5	88·0	0·291
C	2·5-100·5	2·5 cm removed at every 10th cm of the core	75·5	114·1	0·182
E	1312·5-1398·0	2·5 cm removed at every 10th cm of the core and 1327·1330·5 removed	63·0	141·5	0·273

Chemical procedure for the extraction of beryllium from the sediments

Samples A and B. In order to obtain samples of high specific activity, the chemical extraction of beryllium from the samples *A* and *B* was carried out without the addition of any stable ^{9}Be as carrier. The chemical procedure was established from analyses of a synthetic mixture representative of the ocean core and of small sediment sections with ^{7}Be activity added as a tracer, and is described below :

The sediment sample was treated with 500 ml (12N) HCl and 250 ml (15·5N) $HN0_3$ and heated in order to destroy organic matter. The nitrates were then removed by repeatedly boiling the sample with concentrated HCl and then drying it.

Next, the semi-dry residue was treated with 300 ml (12N) HCl and boiled for 15 to 20 minutes. It was then diluted with 300 ml water and again heated to the boiling point. After allowing the insoluble residue to settle down, the liquid portion was decanted and the residue was washed repeatedly with 100 ml (6N) HCl, till it was free of iron. The filtrate (*L*) is thus obtained.

The residue was then boiled with 120 g NaOH (Merck) in a glazed silica dish for 15 minutes and filtered again. This resulted in a filtrate (*M*) and a residue of 5-10 g of undecomposed material. This was fused with about five times its weight of Na_2CO_3 (Merck), dissolved in 100-150 ml HCl and designated as solution (*N*).

The solutions (*L*, *M* and *N*) were mixed together and heated to drive off dissolved carbondioxide. The hydroxides were then precipitated from the solution at pH $\sim$ 8 in order to get rid of sodium salts, and then dissolved in 200 ml HCl. The solution was twice evaporated to dryness with HCl, thereby making silica insoluble. The residue was later boiled with 400 ml (1 + 1) HCl and filtered, resulting in the filtrate (*O*) and a residue consisting mostly of silica. The residue was then moistened with sulphuric acid and heated with hydrofluoric acid to remove silica. When the removal of silica was complete, the remaining residue was thoroughly fumed with sulphuric acid, ignited and fused with sodium carbonate. The fused mass was dissolved in hydrochloric acid and recombined with the filtrate (*O*).

From the filtrate (*O*), group III was precipitated by NH_4OH at pH $\sim$ 8 and dissolved in 500 ml (6N) HCl. Iron was then extracted by shaking the above solution with 1 litre of ether. The removal of aluminium and titanium was carried out by the GOOCH and HAVEN's method (1896) by passing dry hydrochloric acid gas in the ice cold solution containing 150 ml (12N) HCl, 15 g NH_4Cl and 300 ml ether.

The filtrate obtained in the above step was concentrated to 50 ml ; 8 g of disodium salt of EDTA were added and the ph adjusted to 4·5-5·0 by (1 + 1) ammonia. The solution was then shaken for about five minutes with 2·5 ml acetyl-acetone. After adding 100 ml benzene, it was again shaken for ten minutes. This was repeated with three 100 ml portions of benzene. The benzene portions were then combined and extracted with four 175 ml portions of 6 N HCl.

The HCl extract was evaporated to dryness and the organic matter destroyed by treating it with a mixture of hydrochloric acid and nitric acid. The acid solution at this stage contains beryllium along with traces of iron and other impurities. A cupferron extraction was made by adding 10 ml of 6 per cent cupferron solution to the ice-cold solution of beryllium. The cupferrates of the impurities were then extracted by shaking with three 40 ml portions of chloroform. The aqueous layer containing the beryllium was evaporated to dryness and organic matter destroyed with nitric acid. The nitrates were removed by repeatedly boiling with HCl. The sample was then dissolved in 5 ml HCl and deposited for counting.

The efficiency of the chemical procedure was determined from several pilot experiments were ^{7}Be-activity was added as a tracer. The results were quite reproducible with yields of 80 $\pm$ 10%. The acetyl-acetone-benzene extraction cycle by itself has an efficiency of 85 $\pm$ 10%.

The stable ^{9}Be content of the final purified sample was determined fluorometrically using quinizarin reagent (FLETCHER *et al.*, 1946). In core A, the ^{9}Be content was found to be 1·1 $\pm$ 0·25 p.p.m. by weight of the dry core.

In core B, the number of cycles which were found necessary for complete purification were so large, that no meaningful estimate of chemical efficiency was possible. Although the sample proved to contain some ^{10}Be activity, we had to discard the information.

Samples C and E. As can be seen, the chemical procedure adopted for cores A and B is quite laborious and time consuming. This was avoided in the later experiments

with cores C and E and a very much simplified chemistry procedure was adopted. Recent experiments in our laboratory (RAMA and ZUTSHI) have shown that ^{7}Be which arrives in rain water can be quantitatively removed by treatment with (6N) HCl. This proves that ^{7}Be, and therefore ^{10}Be nuclei also, arrive on the surface of the ocean in a form in which they can be easily dissolved in hydrochloric acid. Presumably, therefore, the ^{10}Be nuclei are only adsorbed on the surface of the sediment particles and do not form part of any crystal structure. This suggested the possibility of avoiding a complete decomposition of the core material and extracting an appreciable fraction of ^{10}Be by simply leaching the sediment with hydrochloric acid. The procedure adopted for core C and E, therefore, differed from the one used for cores A and B in the following ways :

(1) 5 mg stable BeO were added as carrier,

(2) The organic matter was decomposed by heating the material at 500°C for 2 hours in a muffle furnace,

(3) After the removal of organic matter, the core was leached with four 190 ml portions of 12 N HCl and subsequently washed with (1 + 1) HCl until the absence of colour indicated complete removal of iron.

(4) Acetyl-acetone-benzene extraction was carried out directly on the solution after adding 400 g of disodium salt of EDTA (ethylene-diamine-tetra-acetic acid),

(5) The chemical efficiency of extraction of beryllium from the hydrochloric acid wash was obtained by fluorometric determination of the beryllium contents and found to be $76 \pm 5\%$ and $60 \pm 5\%$ for cores C and E respectively.

Since it is not yet known what fraction of the ^{10}Be in the core can be removed by this simplified procedure, we have used this method so far only for determining the ratio of the activities between the different sections of the core. All samples were deposited on sample holders as described below and their activities were counted separately.

Deposition of samples

The purified samples were deposited on a platinum foil in the following manner. A cavity of about 6 mm diameter and 3 mm depth was made at the centre of a platinum foil by polymerizing a viscous celluloid solution. The beryllium sample was then transferred to the cavity and evaporated to dryness under an infra-red lamp. The organic matter was destroyed by slowly heating the foil electrically. To bind the powder, a drop of diethylene glycol was added, the foil was heated again and finally brought to about 1000°C. The sample was then covered with a thin film of collodion and gently pressed so that it occupied the desired area.

In order to make sure that no radioactive contamination from the chemicals and from dust, etc., entered the process, several blank sources were prepared under conditions identical with those employed for the core samples. It was found necessary, in order to avoid air-borne contamination, to deposit the sources in a dust-proof glove box. The last stages of purification were carried out in micro-wares in order to keep the quantity of chemicals to a minimum. The possible activity contributed from chemicals was checked by counting sources of (stable) beryllium oxide after a chemical purification. The blank samples did not show any measurable activity.

The counting equipment

The counting system employs a small mica end-window counter (anode length ~ 7 mm and diameter ~ 6 mm), with a buffer volume to ensure long term stability. The counter has the conventional shielding with 1 in. mercury 4 in. iron and 2 in. lead and is operated in anti-coincidence with 13 Geiger counters, each 15 in. long, cylindrically surrounding the end-window counter and an additional layer of 6 Geiger counters on the upper half of the cylindrical anti-coincidence array. Dry batteries supplied the high voltage for the counters. The counter voltages were checked every 8-12 hours by an examination of the pulse heights on an oscilloscope. The coincidence pulses were recorded simultaneously with the anti-coincidence pulses in order to check the counter performance during a run. In order to ensure a fixed geometry, the source was mounted on a copper cap which fitted tight against the window of the counter.

The counting unit had a high stability throughout the experiments. During the total operation for ~ 1400 hours, the mean coincidence rate was found to be $27{\cdot}7 \pm 0{\cdot}15$ counts per hour. In a total of 55 individual counting runs, the coincidence rates for 44 runs agree with this value within one standard deviation and for the remaining 11 runs within two standard deviation.

The background counting rates were always taken with the source holder cap in position and lay between 7·5 and 9·5 counts per hour depending on the source holder which was employed. Platinum foils showed a variable activity from batch to batch ; therefore, the source holder and the platinum foil used in an experiment were counted before the sample was mounted.

The counter geometry was determined by counting a standard ^{204}Tl source (prepared in comparison with a standard RaE source) under conditions identical with those employed for sample counting. The counting efficiency in each case was calculated by taking into account the absorption in the window and in the covering film as well as the back scattering effect due to the support.

EXPERIMENTAL RESULTS

The Be0 contents of the final samples obtained after the chemistry procedure, and the details of activity measurements of the four samples are summarized in Table 2. The chemical efficiencies and the calculated concentrations of ^{10}Be atoms/g of core material, using a half-life of 2·7 million years are given in Table 3.

The chemical efficiency in core A is estimated from the pilot runs carried out with ^{7}Be activity as a tracer. In case of cores C and E, the chemical efficiency for the extraction of beryllium from the hydrochloric acid wash is known from the recovery of the carrier ; the proportion of ^{10}Be recovered in the leach to that which remained behind is, however, not known as yet, and therefore we have multiplied the chemical efficiencies in cores C and E by an unknown factor ϵ, which is however assumed to be the same for the two samples. The approximate value of ϵ can be estimated from comparison of the observed disintegration rates in cores A and C which come from neighbouring sections of the core ; it is about 0·5, which shows that one can recover approximately 50% of the ^{10}Be nuclei by treating the core material with hydrochloric acid.

For ascertaining the nature of the radioactive substance, we subjected the samples to an additional chemical cycle. The four samples A, B, C and E were combined.

The combined sample was subjected to a purification by a different chemical procedure (HEFT and LIBBY, 1955), which is also known to be highly specific for the extraction of beryllium. The Be $(OH)_2$ was precipitated by adding ammonia and was converted to basic beryllium acetate by dissolving it in acetic acid and evaporating the mixture to dryness. The resulting basic beryllium acetate was dissolved in chloroform and

Table 2

Core section	*Wt. of BeO deposited for counting, mg*	*Net counting rate per hour*	*Counting efficiency, per cent*	*Self absorption in the source per cent*	*Total disintegration rate per hour*	*Disintegration rate per hour per mg BeO*
A	0·15 ± ·02	5·5 ± 0·76	27 ± 2	~0	20·4 ± 3·2	
B	0·45 ± ·05	3·3 ± 0·6	27 ± 2	~0	12·2 ± 2·4	
C	3·8 ± 0·25	3·9 ± 0·7	25 ± 2	17 ± 2	18·8 ± 3·7	
E	3·0 ± 0·25	2·3 ± 0·9	25 ± 2	13 ± 2	10·6 ± 4·2	
Total A, B, C, E	7·4 ± 0·36	—	—	—	62·0 ± 6·9	8·4 ± 1 average

Table 3

Core section	*Dry* weight, g*	*Total disintegration rate per hour (d.p.h.)*	*Chemical efficiency, per cent*	*^{10}Be concentration atoms/g core*	*Mean depth below ocean floor, g.cm^{-2}*
A	65·7	20·4 ± 3·2	68 ± 14†	(1·56 ± 0·43) × 10^{10}	31·2
B	79·2	12·2 ± 2·4	"uncertain"	—	368·0
C	111·8	18·8 ± 3·7	(76 ± 5) ϵ	$1/\epsilon$ (0·75 ± 0·15) × 10^{10}	8·5
E	138·6	10·6 ± 4·2	(60 ± 5) ϵ	$1/\epsilon$ (0·43 ± 0·17) × 10^{10}	350

*These are obtained by reducing the dry weights, as given in Table 1, by 10 per cent in samples A and B and by 2 per cent in samples C and E to correct for the fraction removed for fluorometric determinations.

†Sample A went to one additional acetyl-acetone cycle with an estimated efficiency of 85 ± 10 per cent.

the chloroform solution was evaporated to dryness. The residue was heated with nitric acid in order to destroy organic matter. The beryllium nitrate was converted into chloride, ignited and deposited on the sample holder. In this combined and repurified sample a total of 4·85 ± 0·1 mg. BeO was deposited for counting which showed a net counting rate of 6·2 ± 0·8 counts per hour. Under the conditions of source mounting, the counting efficiency and self-absorption were 25 ± 2% and 35 ± 2% respectively. The specific activity is, therefore, 7·9 ± 1·2 disintegrations per hour per mg BeO. This is to be compared with the combined specific activity of 8·4 ± 1·0 d.p.h./mg BeO (see Table 2) averaged over the four samples before the acetate chloroform cycle. Since the two measurements agree within statistical errors, this test confirms the conclusion that the measured activity is due to ^{10}Be.

The absorption measurements were carried out on the purified sample with 28·2 and 56·4 mg cm^{-2} Al absorbers. They yielded a half-thickness of 22 ± 7 mg cm^{-2} Al. Since in our counter geometry the absorption coefficient for soft β-rays can be expected to depend not only on energy but also slightly on geometry and since an artificial ^{10}Be source, was not available, we determined the expected half-thickness for ^{10}Be β-radition indirectly, in the following manner.

It has been shown by several investigators (SIRI, 1949, GLEASON *et al.*, 1951 ; LIBBY, 1956) that over a large energy range (0·1-3·5 MeV), the absorption half-thickness $T_{\frac{1}{2}}$ can be expressed as a function of the maximum β-energy by a single relation

$$T_{\frac{1}{2}} = K E^X, \text{ where } K \text{ and } X \text{ are constants.}$$

In order to determine the values of these constants for our counting geometry, we determined the half-thicknesses for the absorption of radiation from artificial ^{35}S ($E_{max} = 0{\cdot}167$ MeV) and from Tl^{204} ($E_{max} = 0{\cdot}76$ MeV) sources. These measurements yield $39{\cdot}5 \pm 4{\cdot}0$ and $1{\cdot}5 \pm 0{\cdot}09$ for K and X respectively, when E is expressed in MeV and $T_{\frac{1}{2}}$ in mg cm^{-2}. This is in very good agreement with the results of LIBBY (1956). The observed half-thickness of 22 ± 7 mg cm^{-2} correspond to a maximum β-energy of $0{\cdot}68 \pm 0{\cdot}2$ MeV, which is consistent with the value of 0·55 MeV for ^{10}Be β-radiation reported in the literature.

INTERPRETATION OF RESULTS

Apart from the fact that in our core samples, the ^{10}Be activity seems to decrease with increasing depths, we have no evidence as yet, as to whether the samples studied by us represents an accumulation of marine sediments which has remained undisturbed for several million years. Nevertheless, we shall here make the assumption that we are dealing with an undisturbed core.

The question as how to verify such an assumption experimentally to a certain degree has been discussed by PETERS (1957). We shall further assume, and again the verification must await confirmation by future experiments, that the deposition of ^{10}Be at the place, where the core sample was taken corresponds reasonably well to the average deposition of ^{10}Be over the surface of the earth. If these assumptions are granted, we can derive some information from the measurements made so far.

At first we try the hypothesis that the sedimentation rates as well as cosmic-ray intensity have remained constant ; we can then by applying the relations derived by PETERS, calculate the sedimentation rate S and the present day deposition rate of ^{10}Be nuclei, n_0 as a function of the ^{10}Be concentration $p\,(x)$ in a layer at a depth x g/cm^2 below the ocean floor :

$$S\,p\,(x) = n_0 \exp\,[-\,x/(\lambda S)]$$

from which one obtains,

$$S = \frac{x_3 - x_1}{\lambda \log\,(p_1/p_2)} = 0{\cdot}155 \text{ mg/1000 years}$$

$$\text{and } n_0 = S p_2 \exp\,[x_2/(\lambda S)] = 2{\cdot}55 \times 10^6 \text{ } ^{10}\text{Be atoms/cm}^2 \text{ year}$$

where the suffixes 1, 2, and 3 refer to the cores C, A and E respectively and $\lambda = 3{\cdot}9$ million years is the mean-life of ^{10}Be.

The value of S corresponds to an increase in the sediment layer at the rate of 5·5 mm/1000 years, which is to be compared with the currently favoured estimates lying between 1-3 mm per 1000 years. The value of n_0 agrees well with the calculated value $2{\cdot}35 \times 10^6$ ^{10}Be nuclei per cm^2 per year (PETERS, 1957), on the basis of present day ^7Be concentrations of rain water. The errors in the measured concentrations permit an estimate of a lower limit for S and n_0 of 3·4 mm/1000 years and $1{\cdot}1 \times 10^6$

nuclei/cm^2, respectively ; the errors are as yet too large to obtain an estimate for the upper limit. We conclude that our measurements are consistent with the hypothesis of constant sedimentation rates and constant cosmic ray intensity for about 2 million years.

We can evaluate the results also in another way. We accept the present day deposition rate as calculated from the observations of ^{7}Be concentrations in rain water. We retain the assumption of a sedimentation rate independent of time but allow a linearly verying cosmic ray intensity resulting in a correspondingly varying deposition rate of ^{10}Be in the past. As shown in cited reference, we can evaluate the sedimentation rate S and the change of cosmic-ray intensity β, defined by

$$\beta = \frac{\lambda}{I_0}\frac{dI(t)}{dt} = \frac{\lambda}{n_0}\frac{dn(t)}{dt}$$

(I_0 is today's primary cosmic-ray intensity), by using the relation :

$$\frac{I_0 - I(T)}{I_0} = -\frac{x_3\,\beta}{S\lambda} = \frac{x_3}{x_2}\cdot\frac{n_0 - Sp_2\exp[x_2/(S\lambda)]}{n_0}$$

$$= \frac{(p_1/p_3)\exp[-(x_3 - x_1)/(S\lambda)] - 1}{(p_1/p_3)\exp[-(x_3 - x_1)/(S\lambda)] - (x_1/x_3)}$$

where $T = \frac{x_3}{S}$ is the age of the lowest layer investigated so far. One then obtains,

$T = 2.45$ million years, $S = 0{\cdot}143$ mg/year $= 5{\cdot}1$ mm/1,000 years,

$I(T) = 1{\cdot}051_0$

One can also estimate from the errors of measurement, upper and lower values for these quantities, which can still be reconciled easily with the existing observations :

$T = 3{\cdot}2$ million years ; $S = 3{\cdot}9$ mm/1,000 years ; $I(T) = 0{\cdot}90\,I_0$ and

$T = 1{\cdot}67$ million years ; $S = 7{\cdot}5$ mm/1,000 years ; $I(T) = 1{\cdot}55\,I_0$.

The results are therefore consistent with a cosmic-ray intensity which has remained constant. It could have been 10 per cent lower than today, 3·2 million years ago or it could have been 55 per cent higher than today, 1·67 million years ago.

It must be emphasized here that these results depend on the assumption of a core undisturbed for the past several million years. Only the internal consistency of future measurements can decide on its validity.

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Tata Institute of Fundamental Research, Bombay.

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Composition of the swim-bladder gas in bathypelagic fishes

JOHN KANWISHER and ALFRED EBELING

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Abstract—Measurements were made of swim-bladder size and gas composition on pelagic fish in the eastern Pacific. The physiological problem of vertical migration with a swim-bladder is discussed. It is concluded that some gas-containing fish migrate vertically but that net-collecting data is too fragmentary to determine if such fish are primarily responsible for scattering layers.

THE gas in the swim-bladder of a fish is at the hydrostatic pressure of its depth. This may be 100 atmospheres or more. In contrast, the dissolved gases in the water itself have been introduced at the surface, and total only one atmosphere of tension. Since the increased pressure of the gases in the swim-bladder indicate active secretion, their composition is of great interest. SCHOLANDER and co-workers (1951, 1953) found that in a series of marine coastal bottom fishes, the oxygen percentage increased with depth. Although the percentage of nitrogen decreased, its partial pressure was larger at greater depths, reaching as much as 15 atmospheres. Similar data are presented here for bathypelagic fishes. The problem of vertical migration with a swim-bladder is also considered since these fishes are thought to be a component of the scattering layer.

Material was collected at various depths with the 10 ft ISAACS-KIDD mid-water trawl towed at 2-3 knots (ISAACS and KIDD, 1953) over much of the eastern tropical Pacific, during the Eastropic Expedition of the University of California Scripps Institution of Oceanography. Surface fishes and vertically migrating species were taken under a light at night with a dip net.

Collections with nets are incomplete, possibly because many of the faster-swimming animals escape. The squid and lantern fishes seen in large numbers on the surface at night were almost never captured during the daytime tows below the surface. There may be many faster fishes at all depths that are not represented in such collections. BEEBE's direct bathysphere observations (1935) led him to conclude that there was a much more abundant fish fauna than he had surmised from years of trawling with the best oceanographic collecting equipment available. This imposes a severe limitation on statements concerning the kinds of animals in the various scattering layers.

The ISAACS-KIDD trawl is also limited in that it cannot be opened and closed at depth. There is always the possibility that specimens have entered the net while it was being lowered or raised. Whenever possible control tows were made, in which the net was brought back up immediately without towing it at depth. By comparing the two tows one is more certain which fishes were caught at which depth. Some species appeared regularly only in the deeper net tows. The hatchet fishes, *Argyropelecus lychnus* and *Sternoptyx obscura*, were commonly caught in nocturnal tows at depths greater than 200 metres, but were rare in collections from lesser depths. Other fishes (adult ceratioids, alepocephalids, certain stomiatoids, melamphaids, etc.) were characteristic of the fishes collected in the still deeper tows.

As soon as the trawl was brought on board, the cod end was removed and the contents emptied into trays. The fishes were immediately separated and placed in a bucket of sea water. Those with swim-bladders which had come from any depth were distended with gas and floated to the surface. Several of the non-floating ones (ceratioids, alepocephalids, bathylagids, some myctophids, etc.) were checked for gas both by needle puncture and in a pressure chamber, with negative results.

The techniques were the same as those of SCHOLANDER and VAN DAM (1953). The fish that floated were held underwater and the gas withdrawn through a hypodermic needle into a syringe lubricated with an acid citrate solution. With the needle capped, such a sample could be stored for several hours without appreciable change in composition. Thus, samples could be taken immediately from all of the desired material and analysed when convenient.

The analyses were performed in a syringe analyser (SCHOLANDER *et al.*, 1955) for carbon dioxide, oxygen, and nitrogen to an accuracy of 0·5 per cent of the total volume. Carbon dioxide was always less than 2 per cent, and was not considered significant since it increases on standing and is probably at a very low level in the live fishes. Samples of about 30 mm^3 were transferred from the storage syringe to the analyser. Duplicate analyses were done on all but the smallest fishes which did not contain enough gas.

The volume of gas in some of the fishes was determined before sampling in the apparatus shown in Fig. 1. The fish is placed in the chamber, taking care that no

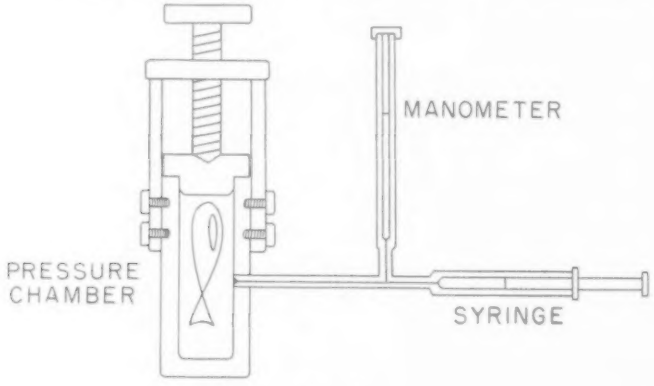

Fig. 1.

bubbles adhere to it. With the chamber brimming with water, the cap is inserted and clamped down. Thus the only gas in the chamber should be that in the swim-bladder of the fish. Pressure is now applied with the syringe until the manometer indicates that the pressure has doubled. HARDEN JONES (1951) has shown that fish probably do not resist such a volume change with their musculature. Applying BOYLE's law, the excursion of the syringe to produce this pressure change will be $\frac{1}{2}$ the volume of the swim-bladder. A small blank is subtracted for the gas in the manometer. It is essential that such a system be as rigid as possible and that bubbles be scrupulously avoided. Fortunately it is easy to check the system by filling the chamber with water only. The blank value is obtained in this way. Such a check was usually repeated after each measurement.

RESULTS

Swim-bladders of surface pelagic species contained 27 to 33 per cent oxygen, only slightly above that of air. This is the same as inshore marine fish taken at the surface. The fishes dip-netted at night, which are believed to have migrated up from depth, had 74 to 91 per cent oxygen. These agree well with the species taken at depth by trawling which also had 53 to 93 per cent oxygen in their swim-bladders.

Below is a list of species divided into these arbitrary categories. A range of oxygen values indicates that more than one individual of the species was measured. The amount of gas is indicated by the per cent of the total volume of the inflated fish made up by the swim-bladder gases at 1 atmosphere at the surface. The compressed gas at depth would be in a much smaller volume.

Table 1.

	Per cent O_2	*Per cent volume of gas*
I. *Surface pelagic species*		
Exocoetidae		
Exocoetus monocirrhus	33	3·5
Cypselurus xenopterus	23–25	
Hirundichthys sp.	33	3·1
Hemiramphidae		
Hemiramphus sp.	29	
II. *Bathypelagic fishes taken at the surface*		
Myctophidae		
Myctophum evermanni	74–91	3·2–5·0
Myctophum spinosum	77–91	4·0–5·5
Myctophum affine	90	
III. *Bathypelagic fishes taken at depth* (*all below* 100 *metres*)		
Sternoptychidae		
Argyropelecus lychnus	72–92	32–65
Argyropelecus affinis	67–93	42–55
Sternoptyx obscura	71–88	
Vinciguerria lucetia	78–90	32–52
Ichthyococcus sp.	77–83	
Melamphaidae		
Melamphaes macrocephalus	73–87	37–65
Melamphaes nigrofulvus	67–77	56
Melamphaes opisthopterus ?	71	
Melamphaes nycterinus	54–93	48–54
Melamphaes cristiceps ?	61–81	
Myctophidea		
Lampanyctus omostigma	89	53
Lampadena bathyphila	85	

Several factors tend to produce errors in the compositions and amounts of gas in the deep fishes. When a fish enters the net it is forced back into the cod end where it probably does not live very long. Since some of the tows lasted several hours, a fish may have been dead nearly this long before being sampled. In such a fish, diffusion will have begun to bring the bladder gases into equilibrium with the rest of the fish and the outside sea water. This will lower the oxygen and raise the nitrogen percentage. Experiments at the surface showed that the oxygen percentage could decrease as much as 10 to 20 per cent in a few hours. Several members of the genus *Melamphaes* were particularly sensitive to this.

The swim-bladders in some of these relatively fragile mid-water fish may have ruptured into the body cavity. Diffusion would then work more quickly to vary the gas composition. Gas would also likely be lost in such a fish. Thus the oxygen content and the amount of gas shown above for the deep fishes can only be considered minimal values. There is little point in computing the size of the swim-bladder at depth from these figures. All that can be said is that the deep fishes had much more gas than those taken on the surface. This is to be expected since a greater absolute amount of gas is necessary to maintain a constant swim-bladder volume at depth due to the pressure.

Oxygen increases with the depth of the fish and at about 200 metres can constitute more than 90 per cent of the gas mixture in the bladder. All deep fish tended toward 80 to 90 per cent. The lower values are probably due to the errors mentioned above.

DISCUSSION

The scattering of sound by horizontally layered marine organisms has been observed over most of the oceans of the world. The identity of the animals that make up these scattering layers had been discussed in several articles (RAITT, 1948; MOORE, 1950). MARSHALL (1951) has shown that fish with functional swim-bladders are widely distributed and may be a principal cause. This is an attractive hypothesis since a gas-filled bladder is a much more efficient scatterer of sound that invertebrates or fishes without enclosed gases.

Since the tissue of fishes is denser than sea water, a gas-filled swim-bladder is necessary if a fish is to adjust itself to neutral buoyancy. An amount of gas equal to about 4 per cent of the body volume of the fish is needed. If these fish migrate vertically, the gas will expand or contract with the changes in hydrostatic pressure. To keep the swim-bladder at the same relative volume, gas must be either secreted or absorbed. PARR (1937) recognized that this places limitations on the amount and speed with which such fishes can change their depth. The secretion of a gas under pressure represents work that must be done by the fish. It is interesting to compute the rate and amount of work represented by some observed migrations in the scattering layer.

A fish must keep its swim-bladder a constant size if its buoyancy is not to change during migration. On this assumption, the work performed in migrating between pressures p_1 and p_2 will vary as :

$$W = 2{\cdot}3\ v\ p_2 \log \frac{p_2}{p_1}$$

where v is the volume of the swim-bladder.

Fig. 2 shows the accumulated work necessary to migrate from the surface to various depths if the swim-bladder is kept constant at 4 per cent of the volume of the fish. The figures are for a 10 g fish with a 0·4 ml swim-bladder. Another atmosphere of gas must be supplied for every 10 metres increase in depth. Since this has to be secreted at continually higher pressure, the rate of doing work increases with depth. This is shown by the increasing slope of the curve with depth. This is only true if the fish keeps in step with the pressure and maintains neutral buoyancy at all depths. MARSHALL (1951, 1954) has discussed the amount of work necessary to migrate vertically. He apparently believes the amount of gas is not increased by secretion in going down, so that the fish gets heavier at great depths.

One can compute the amount of work represented by gas secretion and relate this to what fishes are capable of metabolically. Since many assumptions are necessary the accuracy of such a calculation is open to question. From data of SCHOLANDER *et al.* (1953), a 10 g fish would use about 0·4 ml oxygen per hour. This is equal to 2 g calories under conditions of aerobic oxidation of food stuffs. Anatomically it seems likely that not more than one third of a fish's circulation would go to the

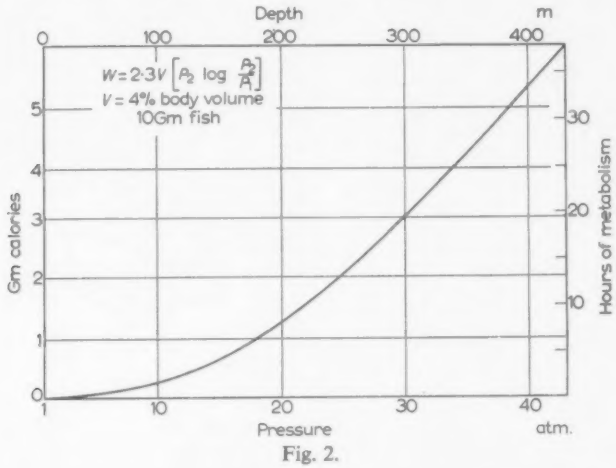

Fig. 2.

swim-bladder. Let us assume that the secretion process is 25 per cent efficient, and that one third of a fish's metabolic work is available for the task. This would allow the fish to secrete an amount of gas equivalent to about 0·15 g calories of work per hour. A scale is included in Fig. 2 representing the number of hours necessary at this rate to attain neutral buoyancy at a given depth. Thus 33 hr would be needed to go to a depth of 400 metres. Such a figure is unrealistic since the scattering layer migration must be made daily. If fishes with swim-bladders make up part of such a layer, their specific gravity probably differs appreciably from sea water at either the top or bottom of their migration. This cannot be too severe a handicap since many species have no swim-bladder. They are successful in spite of having to swim all the time to keep from sinking.

LANTERN FISHES

The various lantern fishes taken with a dip net at the surface at night all had swim-bladders with high percentages of oxygen. SCHOLANDER and co-workers (1951, 1953) only found such a gas composition in fishes taken at a considerable depth. Considering this, the high oxygen values in the present fishes strongly infer that the gas was secreted at depth before they migrated to the surface. The amount of gas was 3 to 5·5 percent of total body volume. This is just the quantity necessary to make the fish neutrally buoyant at the surface. None of these species were caught at depth during daytime tows. This is not surprising since they showed great speed on the surface when chased by squid. If they are part of the most persistent scattering layer, they spend the daytime between 300 and 400 metres. From the metabolic considerations in Fig. 2, it seems unlikely that they could also secrete enough gas

to be weightless at depth. Yet one wonders how the fish would determine the proper amount of gas to secrete at depth to give it the correct-sized swim-bladder, 4 per cent of body volume, at the surface. Whether daily secretion occurs during vertical migration one cannot say without the necessary daytime data. However, the lantern fish do seem to be migrating vertically with a swim-bladder containing gas. Since they are so common they may well be an important sound scatterer.

OXYGEN MINIMUM

The eastern tropical Pacific form which these collections were made has a highly developed oxygen minimum. The dissolved oxygen in the sea water is generally below 0·25 ml per litre from the thermocline at about 100 metres down to 600 or 800 metres. Below this it gradually increases. WINKLER oxygen determinations of less than 0·1 ml per litre are common. In spite of these low values very rich collections were made in this water. In addition, scattering layers were always seen at these depths during both the day and night. One component of the layer appeared to migrate wholly within this region. MARSHALL (1954) has noted that a variety of animals seem to thrive in the oxygen-poor waters of the ocean. It is not clear whether they are the cause or effect of the oxygen minimum.

The hatchet fishes in particular were taken in large numbers in the oxygen minimum, as many as several hundred being caught in one haul. All of them were bloated with large amounts of gas, which was mostly oxygen. HARDEN JONES and MARSHALL (1953) state that the proportion of oxygen in the swim-bladder decreases when fish are kept in low-oxygen water. This is apparently not so for these species.

At depth the partial pressure of oxygen in the swim-bladders of these fishes may amount to 25 or 50 atmospheres, while the oxygen tension in the surrounding sea water is only 1/250 of an atmosphere. The fish maintains its swim-bladder oxygen against a diffusion gradient of 10,000 to 1. MARSHALL (1954) noted that the swim-bladders of deep living fishes have much more developed *retia mirabilia* and gas gland than those of shallow fishes. SCHOLANDER (1954) has shown that the *rete* can function as a counter current diffusion system capable of maintaining a large tension gradient across the bladder wall. Some such special system must be present for blood to flow in and out of the bladder without the gases being lost. It is not known whether the gas is initially secreted at these depths and at these low oxygen concentrations in the sea water.

PARTIAL MIGRATIONS

Since the hatchet fish seemed abundant enough to account for sound scattering, an attempt was made to see if they made a diurnal migration. A series of tows before and after the evening ascent indicated that they were associated with a layer which in the daytime was at 380 to 450 metres. At night it rose to 300 to 350 metres. Since this does not represent a large percentage change in pressure, the fish could probably let the swim-bladder change in volume without having to secrete or absorb during such a migration.

At the same time diffuse scattering at grater depths during the daytime moved up at night and concentrated at about 400 metres. *Melamphaes* with swim-bladders and other black fish characteristic of greater depths were caught here at night.

There are not enough daytime hauls to be certain such species are at greater

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depths. However, collection records of past Scripps Institute of Oceanography expeditions indicate that these species are caught at shallower depths at night than during the day.

Many mid-water fish with swim-bladders seem to perform partial vertical migrations that do not carry them all the way to the surface. These movements may be limited by the amount of distension the swim-bladder can withstand. For a given fractional change in pressure, a deep fish has much more vertical range than a shallow one. HARDEN JONES (1952) has shown that some fresh water fishes can stand a 20 per cent change in pressure without compensating. This may also be the case for these marine fishes.

CONCLUSIONS

(1) Measurements were made of the composition and amount of swim-bladder gases in some pelagic fishes of the eastern Pacific. In deep fishes the oxygen content approached 80 to 90 per cent of the gas. In strictly surface fish the gas contained slightly more oxygen than air. Some fishes taken at the surface at night had high oxygen. The gas was thought to have been secreted at depth since it was from species that are known to migrate vertically.

(2) Net tows indicated that some gas-containing fishes are associated with scattering layers which rise but do not come all the way to the surface at night.

(3) Energy considerations make it unlikely that neutral buoyancy can be maintained by gas secretion during very extensive diurnal vertical migrations.

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LETTERS TO THE EDITORS

Fossil land shells from deep drill holes on western Pacific atolls*

(*Received* 14 *March* 1957)

SHELLS of four species of minute land snails have been recovered from drill holes on Bikini, Eniwetok, and Funafuti Atolls in the western Pacific. All belong to the genus *Ptychodon*, represented today by many species that, almost without exception, are found on forested islands well above sea level. (The fossil species are described in a paper being submitted to the "Journal of Paleontology.") Two of the species are Miocene in age, the others Pleistocene or Recent. The manner of deposition of the shells is not known. The two younger species (at depths of 170 and 450 feet) occur in leached zones and are thought to have been deposited in cavities in the uplifted limestone, in which event they could well be considerably younger than the enclosing rock. The two Miocene species (at depths of 825 and 1810 feet) occur with varied marine faunas that apparently were deposited close to the upraised mass on which the land shells lived. These older species are thought to be of the same age as the enclosing rock but younger than nearby limestone at a higher elevation. The occurrences lend support to the belief that in past times many of the present-day sea level atolls periodically stood above sea level and functioned as steppingstones in the dispersal of life in the Pacific.

Cores and cuttings obtained from drill holes in the Marshall Islands and on Funafuti have revealed zones in which the aragonite of corals and most mollusks has been partially leached, leaving molds, or recrystallized to calcite, a more stable form of calcium carbonate. Emergence of the reef seems to be the most reasonable way to explain the distribution of the consolidated and recrystallized intervals in the sections drilled. Alteration of this sort can be accomplished under atmospheric conditions, for the solvent effects of rainwater acting through a soil zone upon limestone are well known. After water leaches the limestone and becomes saturated, any relatively small changes such as evaporation in cracks or fisures will result in deposition of calcite in veins, as a coating in cavities, or as a recrystallization within the rock.

Tropical marine waters are saturated with calcium carbonate and are unable to dissolve limestone except under the specialized conditions found at intertidal levels, which of course are not effective within the rock mass. Any movement of connate waters below sea level, either because of compaction of limestone by weight of overlying sediments, or because of convection induced by heat from the underlying basaltic foundation, should not result in solution of limestone because the connate waters are already saturated.

The leached zones are thought, therefore, to record periods when the tops of the atolls stood above the sea for appreciable lengths of time (LADD, TRACEY, and LILL, 1948 ; LADD *et al.*, 1953 ; EMERY *et al.*, 1954).** In the deepest holes drilled on Eniwetok three such leached zones have been recognized, the deepest hole on Bikini shows two, Funafuti only one (HINDE, 1904).

The emergence that produced the uppermost zone leached at Bikini and Eniwetok were undoubtedly due largely to Pleistocene eustatic movements of sea level, although slight differences between the two suggest possibly different rates of subsidence. The deeper zones at about 1100 (335 metres) feet at Bikini and Eniwetok correspond closely enough to suggest either an eustatic movement for which there is no other known evidence, or an uplift of the sea floor on a scale large enough to encompass islands 200 miles (322 kilometres) apart. The section of more than 1100 feet drilled on Funafuti is all post-Miocene and nearly twice as thick as that found under Bikini and Eniwetok. The post-Miocene section of Bikini is only slightly thinner than that of Eniwetok but at Jaluit Atoll, in the same island group, Miocene fossils were found in pebbles in

*Publication authorized by the Director, U.S. Geological Survey.

**Since this was written, Miss ESTELLA B. LEOPOLD has obtained dense concentrations of pollen from the Miocene section drilled on Eniwetok Atoll; these occurrences strongly support the postulated emergence. H. S. L.

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blocks of coral conglomerate thrown upon a reef flat by waves (YABE and AOKI, 1922), suggesting that the Miocene lies much higher there and that the post-Miocene is accordingly thin. These differences suggest that local changes of level are quantitatively more important than eustatic shifts for Funafuti. Emergences during the Pleistocene were of limited duration but the duration of the older emergent periods and the exact heights of the emergent parts of the reefs cannot be determined accurately because unknown amounts of limestone may have been removed by subaerial erosion.

U.S. Geological Survey
Washington 25, *D.C.*

H. S. LADD and J. I. TRACEY, JR

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On the biogeochemistry of igneous detritus*

(*Received* 21 *March* 1957)

THE cycling of detrital igneous minerals within the sphere of planktonic filter feeders may account for scarcity of such particles in the aqueous medium of the pelagic environment, beneath which some 15 per cent or more of igneous grains are found in clays.

The author was attracted to the body contents of salps (planktonic filter feeders) during an attempt to use the animals as a source of supply of natural pelagic diatom frustules. Salps appear to be efficient natural pumps filtering diatoms, silicoflagellates, radiolaria, detrital igneous matter, colloidal particles, and similar material from the aqueous environment.

The eupelagic clays of the Northeast Pacific Ocean contain some 15 per cent or more by weight of quartz (GOLDBERG and ARRHENIUS, 1956 ; ROBERT W. REX, personal communication) with an abundance of the quartz grains 3 to 10 microns in size. Grains of augite, zircon, rutile, anatase, feldspar, volcanic glass, and other minerals are also present in the eupelagic sediments. Regardless of the origin of these detrital igneous particles, the question arises as to where in the overlying water and its suspended load such grains are present.

The study of suspended matter and particle distribution in the sea has been primarily concerned with problems of organic production and light attenuation. The separation of the suspended load has been achieved by filtering sea water through suitable membranes, with attempts at determining the ratio of organic to inorganic matter and the chemical as well as the mineralogical composition of the filterable material (ARMSTRONG and ATKINS, 1950 ; GOLDBERG *et al.*, 1952 ; ATKINS and JENKINS, 1954). ATKINS and JENKINS (1954) subjected the particulate matter filtered from several litres of English Channel water to microscopic examination and found very little actual igneous minerals other than clay particles. According to them, an occasional grain of quartz or cordierite was found. On the other hand, when the filtered suspended load was incinerated, the residue was found to consist of the minerals quartz and cordierite, along with some micacious matter. According to the authors, broken grains of feldspar (orthoclase), as well as a fragment of tourmaline, were present.

*Contribution number 207 of the Department of Oceanography of the University of Washington.

In this laboratory, up to 10 litres of integrated Pacific open-ocean water were filtered through molecular filters of approximately 0·5 micron average diameter. Aside from the organic constituents, dark particles of hydrated oxides of iron were fairly abundant but practically no igneous grains were found. Salps collected from pelagic environments in the Pacific were individually washed and their body contents were examined. The nuclei of a few salps were treated at a time to decompose the organic matter and dissolve the silicious frustules which were abundant, as well as the particulate hydrated oxides of iron. This was accomplished by treating the nuclei with hydrogen peroxide followed by hydrochloric acid and mild treatment of hydrofluoric acid. In some cases the organic matter was decomposed by ignition below red heat and the ash was given the acid treatment. The residue was collected on millipore filters, washed with water, and the water-free membrane was rendered transparent for microscopic examination. Although some of the mineral particles, especially those of a few microns in size, may have been dissolved during the process of decomposition the residue was found to consist of quartz grains, which were invariably the most abundant of the igneous constituents. A few grains of feldspar were frequently encountered and occasionally a grain of augite, hornblende, and/or other dark minerals were present. In some samples, especially those collected off the Gulf of Alaska, specks of volcanic glass were frequently found in the body contents of the organisms.

The difficulties involved in quantitative separation and recovery of particles a few microns in diameter from the body contents of the organism, along with the scarcity of information on salps and other planktonic filter feeders concerning their pelagic distribution, population density, and filtering rates, makes it impractical to discuss the problem quantitatively at present. Nevertheless, the present bits of investigation and those of ATKINS and JENKINS (1954) indicate that particulate igneous minerals are primarily incorporated by various organisms of the ocean and thereby isolated from sea water. A pelagic filter feeder one millimetre or less in size may ingest several igneous particles of a few microns in diameter in order to utilize the organic slime adherent to their surface. Planktonic filter feeders may therefore become powerful biogeochemical agents in cycling the igneous detritus within their sphere, leaving the aqueous environment of the open ocean practically free of such particles. The net loss of igneous detritus to the aqueous medium and its ultimate incorporation in the sediments may result after the death, sinking, and decomposition of the organisms.

I am indebted to Mr. LEO BURNER and Dr. H. F. FROLANDER for providing samples of salps collected from pelagic environments and Mr. Y. R. NAYUDU for his assistance in the mineralogical identification.

Department of Oceanography SAYED A. EL WARDANI
University of Washington

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Oceanographic observations by the bathyscaph* *Trieste* (1953–1956)†

JACQUES PICCARD‡ and ROBERT S. DIETZ**

(*Received* 24 *April* 1957)

Abstract—The bathyscaph *Trieste*, a radically new type of submersible craft analogous to a "blimp", permits manned descents to the deep sea floor for the first time. Bathyscaphs appear destined to remain the only type of craft with this capability. Although the primary promise of this craft is for oceanographic research, to date it has been necessary to concentrate on development and safety, rather than on research, in order that its full potentialities can be realized. Thus, scientific results are as yet meagre but sufficiently interesting to summarize here.

A brief description of the bathyscaph principle is given, followed by a summary of physical, biological, and geological observations, which have been made thus far. The special advantages of the bathyscaph over conventional oceanographic ships are mentioned. These are : (1) visual inspection of the deep water layers, and especially of the bottom, (2) visual control of sampling, (3) elimination of the need for long electric cables when using electronic equipment.

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BRIEF DESCRIPTION OF THE BATHYSCAPH *TRIESTE*

THE principle of the bathyscaph *Trieste* is presumably well known to oceanographers and has been described in detail elsewhere (A. PICCARD, 1954, 1956 ; J. PICCARD, 1957), so that only a brief resumé is needed here. To understand how it functions, it is sufficient to consider it as the underwater analogy of a balloon or, better still, a non-rigid lighter-than-air ship or "blimp". As can be seen from Fig. 1, the craft consists of a compartmented flotation hull 15 m long, which can hold 74 metric tons (106 m^3 or 28,000 U.S. gal) of gasoline. Assuming a density of 0·70, this provides a positive buoyancy of 32 tons. The hull is not designed to withstand the great hydrostatic pressure of the deep sea ; instead, water is freely admitted to the hull through openings at the bottom as the gasoline becomes compressed with depth or contracts owing to cooling. The gasoline, being immiscible and lighter than water, continuously floats on top of any water admitted to the hull.

Below the hull is suspended a 2 m inside diameter forged-steel chamber 9 cm thick (thickening to 15 cm near the portholes and door) and weighing 10 tons in air, in which the pilot and a scientific observer can be housed. This hermetically-sealed cabin is capable of withstanding the pressure at 6000 m ; hence, the *Trieste* is designed to reach about 99 per cent of the sea floors of the world — i.e. she is only restricted from trench depths. Entrance into the cabin is made by descending a vertical air lock or "sas" from topside into the cabin through a hatch 43 cm in diameter; the air lock is flooded during descent and blown out with compressed air upon surfacing. The cabin

•*Bathyscaph* is written *bathyscaphe* in French and this spelling has often been transferred to English. However, the final syllable is pronounced with a short *a* ; hence the spelling used here is preferable.

†This paper was prepared by DIETZ on the basis of information furnished by and discussion with PICCARD. DIETZ has taken no part in the dives mentioned in this paper but has simply assisted in making the oceanographic observations a matter of scientific record.

Note added in proof : Since this paper was submitted, the *Trieste* has made a series of U.S. Office of Naval Research sponsored dives in the Tyrrhenian Sea off Italy during the summer of 1957. DIETZ took part in the *Trieste* dive No. 27 to a depth of 1100 m off Capri. The results of these dives are not considered in this paper.

has both fore and aft portholes made of truncated right-angle cones of Plexiglas 15 cm thick, 40 cm wide outside, and 10 cm wide inside. The cabin also contains twelve " lead-throughs " for the electric cables necessary to operate the craft, plus its navigational and scientific equipment, and two lead-throughs for snorkels to conserve oxygen in an emergency when " buttoned up " on the surface.

Submergence is initially effected by taking on water ballast in tanks at the two ends of the hull ; additional negative buoyancy when underwater can be attained, if needed, by valving-off a small quantity of gasoline. The craft can be made to ascend at will by jettisoning some of the 10 tons of iron shot contained in two fore and aft silos. Horizontal manoeuverability for short distances under water is accomplished through the separate or combined use of two propellers located on top of the hull which thrust the craft slowly forward or backward.

The bathyscaph was invented by A. PICCARD (father of the first-named author) to permit manned descents to the deep sea floor, thus allowing the oceanographer to accompany his instruments and to make visual inspections. Although the bathyscaph is the undersea version of a "blimp", a noteworthy difference in future potential should be emphasized. The blimp has, of course, become almost obsolescent in the air and is now limited to very special purposes ; it has been supplanted by propeller and jet-driven heavier-than-air craft. But it seems inevitable that the bathyscaph will be uniquely able to navigate in the deep sea and will remain the oceanographer's only hope for manned deep submergence in a free craft. The design depth of the *Trieste* is 6000 m (with a safety factor of about 3) or about 30 times as deep as that of the conventional World War II submarine, and it is unlikely that a submarine can be sufficiently reinforced to go much deeper than 1 mile. The deepest dive of the *Trieste* to date is 3700 m (12,400 ft), but this limitation has been imposed by the depth of the Mediterranean Sea around Italy.

Although the oceanographic results obtained to date are meagre, it seems worth while to bring them to the attention of oceanographers. As with any new and experimental craft, it has been necessary to concentrate on development of the craft and its accessories and also to demonstrate that dives are not unduly hazardous or adventurous. As of 1956, twenty-two dives have been made with the *Trieste* and more than forty with the FNRS-2 and FNRS-3 without any casualties.

It should be pointed out that very limited funds have been available for the *Trieste* project, so that it has not been possible to install specialized scientific equipment or even all the desirable control and navigational devices. For example, there has been no exterior camera, and only in 1955 was it possible to obtain a small echo sounder.

DIVES OF THE *TRIESTE* (1953–1956)

The *Trieste* was constructed in Trieste between March 1952 and July 1953. Her realization was made possible through the generous support of Italian and Swiss patrons (authorities, foundations, industries, and private citizens). The craft was then moved to the Navalmeccanica shipyard at Castellammare-di-Stabia (near Naples) which kindly offered collaboration in her berthing and maintenance and where deep water was conveniently near. The *Trieste* was launched for the first time on 1 August 1953 and four dives were made near the shipyard and in the Bay of Naples. The first two very shallow submersions are recorded as dives only because they were the " baptismal " ones.

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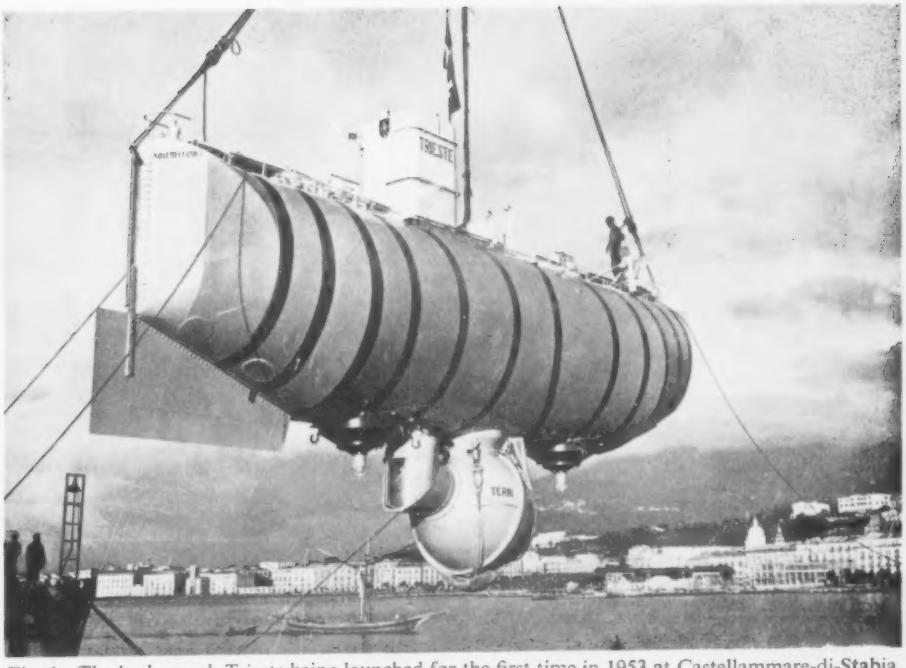

Fig. 1. The bathyscaph *Trieste* being launched for the first time in 1953 at Castellammare-di-Stabia, Italy (Photo TRONCOME, Naples).

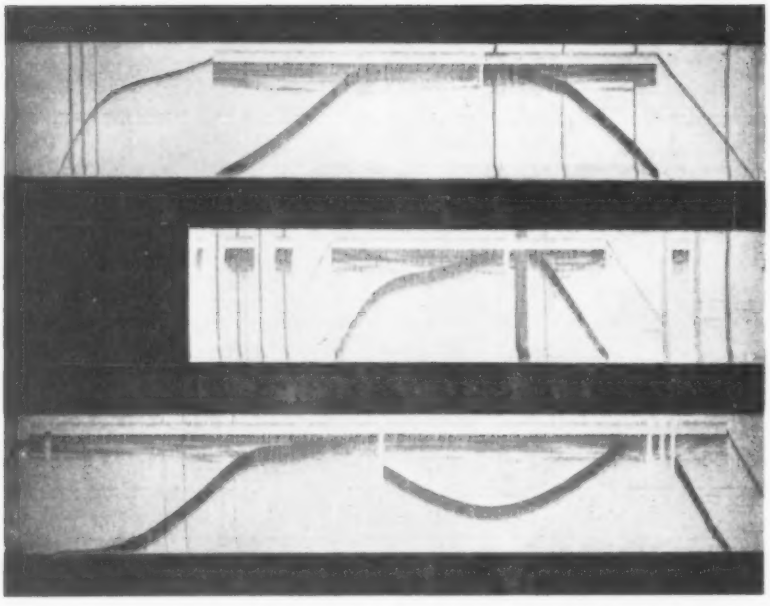

Fig. 2. Some concept of the method of landing on the bottom (on the left) and taking off (on the right) can be obtained from these photographs of echo sounder traces. For ease of understanding, the echograms are presented upside down. In actuality, the trace recorded is the bottom " falling up " as the echo sounder approaches the bottom. But when the paper is inverted, one receives the illusion of the bathyscaph making a landing. The scale of the echo sounder is 50 fm (90 m) for the full paper width : the heavy trace is on an 0–100 m scale when the thin trace is phased in on a 100-200 m scale. What appears to be a " mushy " bottom echo is the outgoing ping followed by reflections from parts of the substructure of the bathyscaph. However, a few solitary isolated scatters are also present which are presumably from unseen animals in the water. The vertical lines mark the release of iron pellet ballast. The blank spaces mark intervals when the echo sounder was turned off – sometimes for a long period. The steepness of the trace is, of course, a measure of the rate of descent or ascent.

The top echogram (reading from the right to left) shows the craft rapidly approaching the bottom, on Dive No. 20 to 1100 m, and then, after releasing ballast four times, levelling off and making a gentle contact with the bottom. After a stay on the bottom, some more ballast is released and the bathyscaph rises slowly to about 70 m above the bottom. Following the valving off of some gasoline, the *Trieste* once more settles to the bottom. Later more ballast is dropped and she rises toward the surface.

The centre echogram shows the landing on Div No. 21 at 2000 m, which again was gentle after dropping ballast. It is noteworthy that the bottom could not be detected until the *Trieste* was 150 m from it. Upon landing, the bottom was found to be a very fine soft mud which presumably accounted for the poor reflectivity.

The bottom echogram shows a comparatively rapid landing on Dive No. 22 to 3700 m. The departure for the surface is shown on the left.

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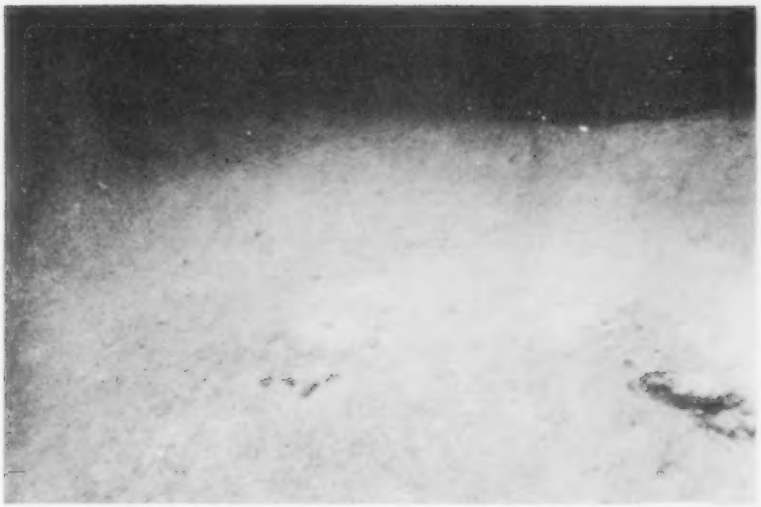

Fig. 3. A view of the sea floor south of the Isle of Capri, taken on Dive No. 20 to 1000 m. At the centre there is a mound with a central hole built by some benthic animal. Photo by J. PICCARD.

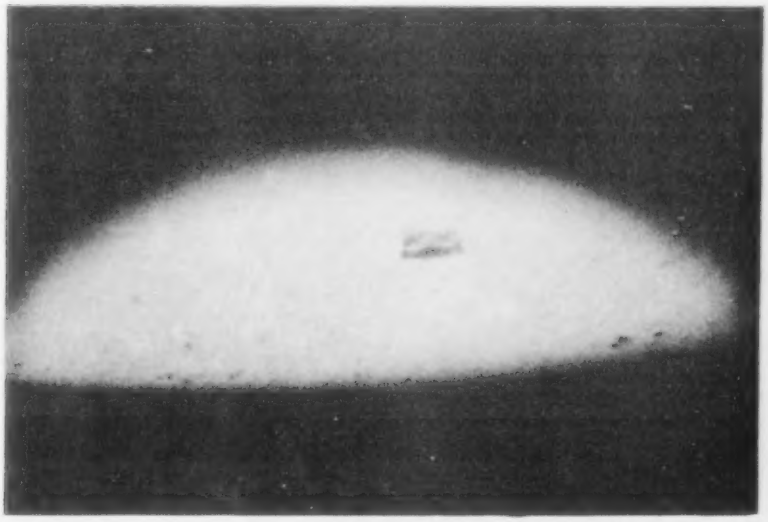

Fig. 4. A a lone rock resting on firm mud bottom, at a depth of 3700 m on Dive No. 22, in the Tyrhennian Sea basin off the Island of Ponza. The anomalous position of this rock, about 2 litres in volume, on an expanse of mud bottom suggests that it may have been rafted. Photo by J. PICCARD.

Fig. 5. A cloud of sediment thrown up to a height of several metres following the jettisoning of some iron pellet ballast on the bottom. Taken on Dive No. 20 to 1100 m, 13 October 1956, by J. PICCARD.

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(1) The first dive — test emersion to 8 m (11 August 1953).

(2) A dive to 16 m (13 August 1953).

(3) A dive to 40 m (14 August 1953) near Castellammare.

(4) A dive to 1080 m (26 August 1953) south of the Isle of Capri.

The *Trieste* was then dry-docked for a thorough examination, after which the following dives were made :

(5) A controlled dive to 15 m (29 September 1953) in the roadstead of Ponza.

(6) A dive to 3150 m (30 September 1953) south of the Island of Ponza.

(7) A dive to 650 m (2 October 1953) south of the Island of Ischia.

All these dives were of an essentially technical and test nature with A. PICCARD and J. PICCARD as the participants.

The following autumn the *Trieste* was put in the water for the third time. Eight shallow dives (Dives No. 8-15) were made in the Gulf of Naples to depths between 50 and 150 m. The weather did not allow the *Trieste* to go outside the Gulf to find greater depths. P. TARDENT, a Swiss zoologist appointed by the " Fonds National Suisse pour la Recherche Scientifique ", and A. POLLINI, an Italian geologist appointed by the University of Milan, participated in two of these dives, as did various other Italian observers. The *Trieste* was piloted by J. PICCARD on all dives. Some bottom samples were taken and a number of interesting observations made in spite of the shallowness of the Gulf of Naples.

In 1955 no dives were made because of inadequate financial aid. On the other hand, many improvements in the bathyscaph were made, such as the installation of new floodlights and an echo sounder.

On 20 September 1956, the *Trieste* was launched for the fourth time. The following seven dives were made with J. PICCARD as the pilot :

(16) A controlled dive to 17 m (29 September 1956) at the entrance to the port of Castellammare-di-Stabia.

(17) A dive to 40 m (2 October 1956) off Castellammare-di-Stabia (Observer : M. KOBR, biologist).

(18) A dive to 150 m (10 October 1956) in the Gulf of Naples (Observer : A. POLLINI, geologist).

(19) A dive to 620 m (12 October 1956) between Capri and Ischia (Observer : A. POLLINI).

(20) A dive to 1100 m (13 October 1956) south of Capri (Observer : A. POLLINI).

(21) A dive to 2000 m (16 October 1956) south of Ponza ; 40° 42′ 45″N, 13° 02′ 15″E.
(Observer : A. POLLINI).

(22) A dive to 3700 m (17 October 1956) south of Ponza ; 40° 37′N, 12° 49′ 58″E.
(Observer : A. POLLINI).

During these 1956 dives the bathyscaph remained under water for a total of 16 hours, four and a half of which were spent on the bottom. The observations below the surface were made over a vertical distance of more than 15 km, always under excellent conditions both in darkness and with the floodlights.

All the deep dives were made possible by the collaboration of the Italian Navy who provided a tug for towing the *Trieste* out to deep water, kept the diving area clear during the dives, and otherwise assisted each dive. It is a pleasure to acknowledge this kind assistance.

As noted above, the dives prior to 1956 were accomplished without the aid of an echo sounder, which made it difficult to anticipate the sea floor landing in time to deballast properly and touch down gently on the guide rope. Hence, the cabin settled into the mud on two of the earlier dives (No. 4 and No. 6), obscuring vision out of the lower porthole. This difficulty was corrected in 1956 with the installation of the echo sounder which has greatly simplified the delicate task of landing on the guide rope and maintaining the bathyscaph suspended a few meters off the bottom. The manner of landing can be seen in Fig. 2.

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BIOLOGICAL OBSERVATIONS

No biologists have participated in any of the deep dives of the *Trieste*, although M. KOBR, a Swiss biologist, has made one shallow dive and P. TARDENT, a Swiss zoologist at the Naples Zoological Station, has made another dive to 125 m in the Bay of Naples. Hence, the deep observations have been made entirely by non-biologists, so that they may not be exact.

Particularly during the 1956 dives to 1100, 2000, and 3700 m, the bathyscaph traversed zones between 500 to 900 m where the density of life appeared to be remarkable. Hundreds of tunicates could be seen at one time, mainly salpa ($\frac{1}{2}$–1 cm long) which flashed with an almost white luminescence. At times there seemed to be about ten dozen salpa per cubic meter of water. Although these tunicates are quite transparent and have little optical relief, it is possible to see them by an internal bluish spot when the floodlights are lit. On ascending from dive No. 21 at 1100 m, it was possible to follow these salpa all the way to the surface. The same species seemed to be present throughout the entire water column, but this cannot be stated for certain.

Besides these widespread salpa, unicellular and luminescent animalcules in very large numbers have been observed on all dives with the *Trieste*. Most often these have been isolated forms, but chain-like and elongated zooplankton have frequently been seen as well. Coelenterates which have brilliant luminescent spots in their bodies have sometimes been observed. Occasionally, other forms of life appeared in mid-depths, such as siphonophores, medusae (probably *Carmarina hastata*), other hydrozoans, pteropods and once a small colourless shrimp 3 cm long.

With the exception of some common fish on shallow dives (and in two instances fleeting luminescent streaks in deep water which may have been fish), no fish have been seen on the deep dives. Possibly this is because the 1956 dives were made with a

geologist as the scientific observer, so that the descents were made as quickly as possible in order to spend a maximum amount of time on the bottom. As in the water column, life has been sparse on the sea floor on all dives when it was possible to see the bottom. On all the deep bottoms observed and traversed thus far, no fish have been seen.

During shallow dives in the Gulf of Naples, common small fish have repeatedly been seen, notably blennies or gobiids, which find refuge in small holes in the bottom when they are startled, for example, by the dropping of ballast. Similar small holes provide refuge for shrimps and crabs, and they have been seen entering or leaving the burrows. Also in the Gulf of Naples, several forms of echinoderms have been observed — various star fish, sea urchins (notably of the *Dorocidaris* type) as well as some gastropods (e.g. probably *Pleurobranchus testudinarius*). Sea anemones, some annelids (*Spirographis*, *Spallanzanii*), and other common forms of the region have been observed.

On the dives up to 1000 m there has been evidence of the activity of benthic animals; the bottom is covered with trails, and with burrows usually about 1 cm across the opening (Fig. 3). A few bigger holes, and small hillocks which are similar to mole hills, were also present. Such holes and mounds were absent on the deepest dives. A curious phenomenon was noted on Dive No. 21 (2000 m) south of the Isle of Ponza. There, the very fine and soft mud was covered with a very thin layer 5–10 mm thick that appeared to be mold.

The Mediterranean is, of course, a comparatively sterile sea (e.g. the Mediterranean side of Spain has an organic production which is only about one eighth of that on the Atlantic side), so that a rich bottom fauna is not to be expected. Also for this reason, the Deep Scattering Layer is only poorly and sporadically developed in the Mediterranean. This may partly explain why no unusually rich zone of life has been noted at the normal depth of the DSL – i.e. 400–600 m. Further, the warmth of the deep Mediterranean water and the physical barrier imposed by the Straits of Gibraltar on the migration of deep-sea animals that have evolved in the open oceans must greatly restrict deep-sea life in the Mediterranean.

As seen from the *Trieste* the water is never completely clear but always contains a few scattering particles (the so-called sea dust or sea snow) which show up whenever the floodlights are turned on. These particles are unidentifiable, but presumably are largely nannoplankton and organic detritus. Once, in the Bay of Naples, these scattering particles were so abundant that it appeared as though the *Trieste* was driving through a snow storm, but in deep water such particles are sparse. Such scatterers cannot readily be seen in the shallow euphotic zone but this is probably due to the effect of diffuse daylight which obscures the Tyndall scattering effect. It is much easier to see particles in the water in dark surroundings, just as is the dust in the air when a beam of sunlight shines into a darkened room. This Tyndall effect provides remarkable "seeing", so that one can detect very minute animals. With the lights extinguished in deep water a small point of bioluminescence is seen every few seconds.

French bathyscaph divers have reported a most interesting crystal-clear layer of water a few meters or a few decimeters thick and adjacent to the bottom. Although the bottom has always been clear, observers on the *Trieste* have not been aware of

any special clarity as compared with the water layers above, but this may be because their gaze has been intently fixed on the bottom.

PHYSICAL OBSERVATIONS

No current meter has yet been installed on the *Trieste*, but it is nevertheless possible to obtain a rough idea of bottom current velocities, if they are more than a few cm/sec, once visual contact can be made with the bottom so that one has a stationary reference. This can be done by watching scattering particles moving along the bottom, or by watching a cloud of mud stirred up by dropping some ballast. However, no currents have been detected on any of the deep *Trieste* dives, and the water has appeared to be completely stagnant. This may be because of the almost tideless nature of the Mediteranean Sea. A similar lack of current generally has been noted in the Mediterranean by observers on the FNRS-3 although BERNARD (1955, p. 12) reports a bottom current of 5–6 cm/sec at 2118 m off Toulon. This is in striking contrast to the strong currents encountered at depth off Dakar where, for example, HOUOT (1954) reports that once at 750 m the bottom current was strong enough to overcome the anchoring effect of the guide rope and to drag the FNRS-3 along the bottom. In the Atlantic strong currents are also evidenced by the deep Atlantic photographs of ripples and scours (taken, for example, by DAVID OWEN at Woods Hole, BRUCE HEEZEN at the Lamont Geological Observatory and A. S. LAUGHTON at the British National Institute of Oceanography).

On two occasions the descent of the *Trieste* was completely stopped at the thermocline by the denser water lying below it. The first instance occurred at 25 m on Dive No. 3 near Castellammare. On this occasion, the *Trieste* rested on the thermocline for about 15 minutes waiting for the gasoline to cool sufficiently for the *Trieste* to recommence descending to the bottom, which could be seen only 15 m below. However, the craft continued to rest on the thermocline so that, in lieu of jettisoning valuable petrol, the bathyscaph was returned to the surface by jettisoning a small amount of the iron pellet ballast. At the surface, more topside ballast was placed aboard, which then permitted penetration through the thermocline to the bottom. The second instance took place at 50 m on Dive No. 22 (to 3700 m off Ponza). This time a little gasoline was jettisoned after delaying about one half hour, thus permitting descent to the bottom. On both occasions the *Trieste* appeared to rest quietly on the thermocline with no evidence of any oscillations due to internal waves.

In order to make a rough measurement of the transparency of the sea water, the white-painted bottom of one of the ballast silos was watched during a descent with the floodlights extinguished. It finally disappeared completely from sight at a depth of about 600 m, indicating a remarkable clarity for the Tyrrhennian Sea which must compare closely with the Sargasso Sea where supposedly the clearest water in the world is found. The unusual clarity of Mediterranean water is, of course, well known and is evidenced by its blue colour.

When approaching the bottom, the sea floor has generally been found to come into view at a distance of about 15 m, which is, naturally, a function of the strength of the floodlights as well as the clarity of the ever excellent water.

GEOLOGICAL OBSERVATIONS

The bathyscaph has landed on soft and flat bottom on most of the dives made.

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Around the Isle of Capri, however, where there are steep slopes, hard or locally rocky bottom has been encountered. This is true especially of Bocca Piccola, the area between Capri and the Sorrento peninsula, where currents are found. On one occasion, the bathyscaph itself was slowly carried along by a current of about 1 knot until additional gasoline was jettisoned, so that the cabin rested firmly on the bottom.

The deep-sea floor down to 1000 m has been found to be pocked with mounds and burrows, which are obviously due to the activity of benthic animals, but these have not been noted on the deeper dives. No deep ripples or scours such as would result from bottom currents have been noted. On Dive No. 22 (3700 m) a clean rock (Fig. 4) about 2 l^3 in volume was observed resting in the midst of an expanse of mud with no scours around it. This rock must have been rafted on the surface either by ship or naturally before being dropped into this anomalous position.

On Dive No. 20 (1100 m) an electrical short circuit occurred in the cabin after about 1 hr on the sea floor, which made it necessary to leave the bottom for a short time while making the repair. To begin the short ascent about 50 kg of ballast was jettisoned. This rain of iron pellets on the bottom caused a remarkably large billowing cloud of mud (Fig. 5) which quickly reached a height of several metres and enveloped the bathyscaph as it rose off the bottom. Later, a little gasoline was valved off, permitting the craft to return to the bottom. The mud cloud, triggered by this slight rain of iron pellets on the flat bottom, impressively demonstrates how labile some sea floor sediments can be. Also one can more readily accept that turbidity currents are an effective process operating on the sea floor. The lability of the mud is probably due to the fact that clay minerals in the sea do not " weather " into a plastic and adhesive mass like terrestrial soils, but rather adsorb cations and absorb potassium into their lattice.

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As is well known, sound pulses are highly absorbed on soft mud bottom but less so on a firm mud, rock, and sand bottom, in this order. The echo sounder on the *Trieste* generally records the bottom at a maximum depth of 180 m (100 fathoms), but on Dive No. 21 (to 2000 m) the bottom echo was not received until the craft was at a height of 130 m above the bottom (Fig. 2). Upon landing, the bottom was found to be unusually soft and fine-grained.

On Dive No. 22 (3700 m) the *Trieste* landed on firm mud or clay bottom in the basin of the Tyrrhenian Sea although this dive was near to the previous one to 2000 m where a soft bottom was found. This time it is probable that the *Trieste* landed on the top of a small rise of low relief. It is interesting that even this small elevation apparently was sufficient to result in a marked difference in the type of sediment on the bottom. Perhaps the soft sediments in the surrounding region are deposited by turbidity flows, but the top of this small rise is out of the reach of their influence. Possibly, also, the currents here are at times strong enough to waft any newly deposited fine-grained pelagic sediments into the surrounding topographic lows although no current was visible on this date.

The *Trieste* is equipped with a small sediment sampler with which several small samples of the bottom have been dredged up. Most of these are being studied by A. POLLINI, at the University of Milan.

OCEANOGRAPHIC USES OF A BATHYSCAPH

As a craft for oceanographic research, there are three general categories in which

the bathyscaph may be uniquely useful. First and most important, it allows direct visual inspection of the deep-sea and sea floor. This is vitally important, especially when it is realized that nearly all we know about our environment has been learned through our sense of sight. Of course, the camera provides us with some visual knowledge of the deep-sea, but "the eye is closer to the brain". Everyone who has done mid-water photography, particularly in connection with the deep scattering layers, has found diffuse specks and smudges on his film which are presumed to be real scattering objects in the water. However, it was indeterminable whether they are alive and swimming or dead organic or inorganic detritus. Also, the camera is limited to the coverage of small areas which are photographed at random, whereas the bathyscaph observer can scan broad areas seeing as much on a single dive as the area covered by all the sea floor photographs ever taken. In addition he can receive for the first time a detailed impression of the topography of the sea floor, especially features like knolls and small valleys which fall within the spectrum of topographic forms which are too large to be seen by the camera but too small to be resolved by echo sounding. Nevertheless, it will always be important to photograph as well as to observe on any dive in order to bring back a permanent record which can be examined at leisure by various specialists.

Secondly, the bathyscaph potentially enables selective sampling of the deep waters or the sediments with visual control. At present, all deep oceanographic sampling has to be done remotely, blindly, and randomly. The oceanographer's concept of the general environment in which he is sampling and of how his sampler is operating may be far from the actuality. Consider the plight of the geologist or the botanist on land who could not take selective samples. The *Trieste* now can take only sediment samples with no exact control over where they are taken ; but even now one gains an intimate knowledge of the general environment whence the sample was obtained and knows whether the bottom is uniform, and, hence, if the sample is representative. A future and more sophisticated bathyscaph conceivably could be equipped with prosthetic arms and other devices whereby really selective sampling could be accomplished. As a specific example of the value of seeing what occurs while an observation is made, consider the 1912 experiments by HELLAND-HANSEN, who has been widely considered to have shown that sunlight penetrates to 1000 m. He found that blackening took place on a photographic film exposed for 80 min. Yet, we now know if such an experiment had been subjected to visual monitoring, it would, in all likelihood, have been obvious that his measurements were vitiated by the ambient light produced by luminescent zooplankton.

A third use for this unique craft is as a deep, quiet, and stable platform for the scientist and his instruments. The chief value here lies in experiments where one needs elaborate modern electronic devices which are rapidly supplanting the classical mechanical instruments. These generally are not self-contained, so that long electric cables are needed to obtain deep observations. Lowering a 3-mile-long multi-conductor cable from a surface ship is such a formidable task that few such experiments have ever been conducted. Thus, we know very little, for example, about the coherence and quality of acoustic signals at great depth although oceanographic considerations

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suggest that transmitted sound should be much less distorted there. With the bathyscaph, however, the conductor cables need never be more than a few meters in length.

‡6 *chemin des Sorbiers, Lausanne, Switzerland*

****Office of Naval Research (U.S. Navy) London Branch Office, Keysign House, 429 Oxford St., London W.1, England*

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A taxonomic analysis of *Myctophum affine* and *M. nitidulum*, two lantern-fishes previously synonymized, in the western North Atlantic

ROBERT H. GIBBS, JR.

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Abstract—The lantern-fishes currently known as *Myctophum affine* constitute two distinct species. *M. affine* has ctenoid scales, a rounded upper opercle, PLO photophore about midway between pectoral fin insertion and lateral line, and more gill rakers. *M. nitidulum* has cycloid scales, an angulated upper opercle, PLO nearer pectoral insertion, and fewer gill rakers. *M. affine* is a smaller fish and develops caudal-peduncle luminous scales at a smaller size than *M. nitidulum*. No significant meristic differences were found between samples from the western North Atlantic, the Gulf of Mexico, and the Caribbean Sea.

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INTRODUCTION

THE widespread and common lantern-fish known as *Myctophum affine* has, for many years, been in a state of systematic confusion. This has been recognized by recent workers (PARR, 1928; BOLIN, 1939, 1946; FRASER-BRUNNER, 1949), who have partially investigated the problems, but who have been able to solve only a few. Recent collections made by means of a dip-net at a surface light at night have provided material from several areas of the western North Atlantic. These collections have revealed the existence in this region of two species which fit current descriptions of *Myctophum affine*. These are analysed herein.

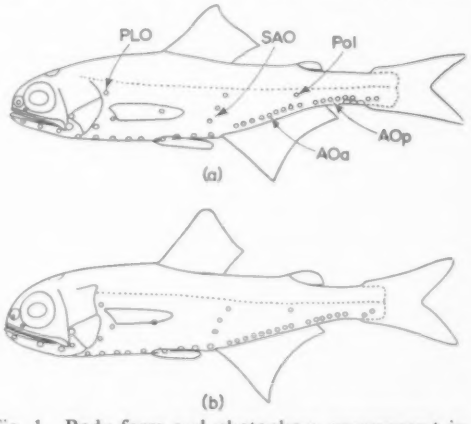

Fig. 1. Body form and photophore arrangement in (A) *Myctophum affine* and (B) *M. nitidulum*. From specimens 49·2 mm and 48·2 mm, respectively, collected at 39° 28′N, 69° 30′W on October 30, 1957. The specimen of *M. nitidulum* lacked caudal-peduncle luminous scales.

METHODS

Counts and measurements have been made in accordance with HUBBS and LAGLER (1947). Designation of photophore groups follows the system used by most current authors and exemplified by FRASER-BRUNNER (1949). Many previous workers have counted all the elements in the dorsal and anal fins of Myctophids. My counts were *principal* ray counts, which do not include three spinous elements in the dorsal fin and two in the anal. For comparison with others, these can be added at the appropriate places in the frequency distributions.

NOMENCLATURE

In the most recent key to the genus *Myctophum* (FRASER-BRUNNER, 1949), any member of this genus with the three SAO photophores (see Fig. 1) in a straight line and with Pol below the adipose fin comes out to *M. affine*. In the collections reported herein, variants were noted which did not correspond to other points in FRASER-BRUNNER's synopsis, and which upheld the suspicion voiced by BOLIN (1939) that certain *M. affine* have ctenoid or crenulated scales. Further investigation has shown that the cycloid and ctenoid forms do, indeed, represent two species, which are distinctly, if subtly, characterized. These species have also been recognized by BOLIN, who will report on them and their nomenclature in a forthcoming publication. He has informed me that the ctenoid-scaled species is the true *M. affine*. The earliest available name for the cycloid-scaled species is *M. nitidulum* (GARMAN, 1899). These names will be used in the remainder of this paper.

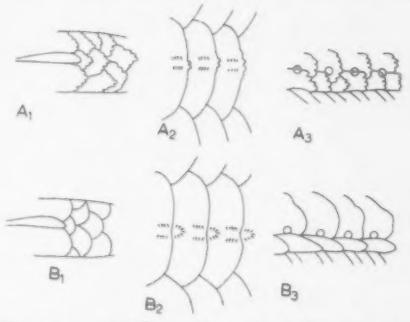

Fig. 2. Configuration of scales of (A) *Myctophum affine* and (B) *M. nitidulum*. (1) Dorsal region behind dorsal fin. (2) Lateral line. (3) Region above anal fin.

TAXONOMIC CHARACTERS

The two species may be easily recognized without reference to counts or measurements. In *M. affine*, except in some specimens smaller than about 25 mm, the scales are ctenoid, strongly so in the mid-dorsal region and the lower part of the sides posterior to the pelvic insertion, but even the large lateral-line scales are at least weakly toothed near the median notch ; in

Table 1. *Frequency distribution of meristic characters of* Myctophum affine *and* M. nitidulum

	Dorsal rays				*Anal rays*					*Pectoral rays*					
	9	10	11	$\bar{x}$	16	17	18	19	$\bar{x}$	11	12	13	14	15	$\bar{x}$
affine	4	84	7	10·0	14	67	14	—	17·0	—	16	113	57	—	13·2
nitidulum	1	63	6	10·1	1	26	37	6	17·7	1	13	60	56	6	13·4

	AOa					*AOp*				*Total AO*					
	7	8	9	10	$\bar{x}$	4	5	6	$\bar{x}$	12	13	14	15	16	$\bar{x}$
affine	—	47	48	—	8·5	9	64	22	5·1	2	38	47	8	—	13·6
nitidulum	1	16	47	6	8·8	8	47	15	5·1	1	16	41	11	1	13·9

	Lateral-line scales							*Upper rakers*					
	36	37	38	39	40	41	$\bar{x}$	4	5	6	7	8	$\bar{x}$
affine	1	5	23	41	23	2	38·9	—	8	73	13	1	6·1
nitidulum	1	4	29	22	12	1	38·6	1	55	12	1	—	5·2

	Lower rakers						*Total rakers*							
	13	14	15	16	17	$\bar{x}$	18	19	20	21	22	23	24	$\bar{x}$
affine	2	16	53	21	3	15·5	—	7	12	43	27	5	1	21·0
nitidulum	19	34	16	—	—	13·9	181	31	12	8	—	—	—	19·1

M. nitidulum, the scales are uniformly cycloid (Fig. 2). The opercular margin of *M. affine* is rounded in its dorsal half, curving in a regular arc ; in *M. nitidulum*, the margin forms a decided angle in its dorsal half (Fig. 1). The PLO photophore in *M. affine* is approximately mid-way between the pectoral insertion and the lateral line, whereas in *M. nitidulum* it is decidedly nearer the pectoral insertion (Fig. 1).

Frequency distributions of certain meristic characters are shown in Table 1. The most significant of these with respect to identification is the number of gill rakers. In *M. affine* the total number is seldom less than twenty-one, in *M. nitidulum*, seldom more than twenty. Other characters show slight mean differences which are, however, not useful in identification. One of these, it should be noted, is the number of AO photophores, upon which much taxonomic weight is placed in other species.

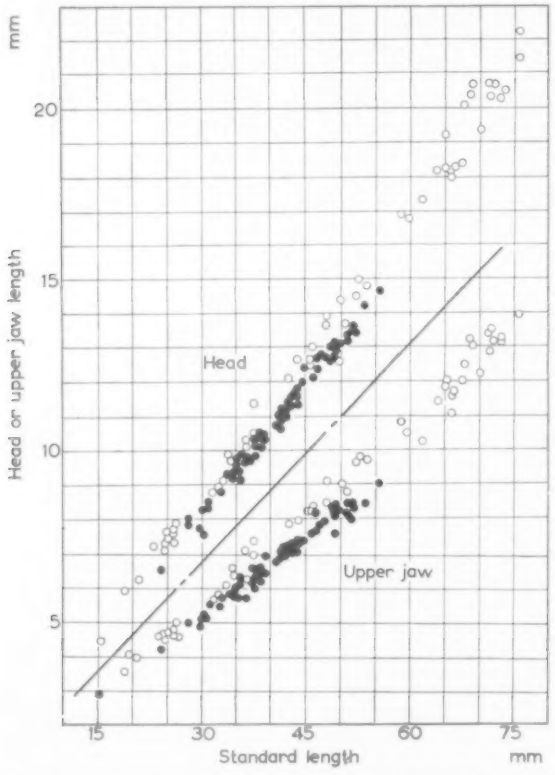

Fig. 3. Head length and upper jaw length plotted against standard length in *Myctophum affine* (black dots) and *M. nitidulum* (open circles).

Eleven measurements of body parts were taken and plotted against standard length. Of these, the two which showed differences worthy of consideration are shown in Fig. 3. The lengths of both head and upper jaw are greater in *M. nitidulum* than in *M. affine*, and the points for each species are rather well-separated.

SIZE AND MATURITY

Table 2 lists the largest specimen of *M. affine* and *M. nitidulum* in each collection used in this study, which contained specimens at least 40 mm long. This shows a

Table 2. Sizes of largest specimens of Myctophum nitidulum *and* M. affine *in each containing individuals* 40 mm *long or longer*

nitidulum				*affine*	
45·8	63·3	68·0	73·1	42·0	52·1
45·9	65·2	71·4	74·6	42·3	52·2
46·0	65·2	71·5	75·1	43·5	53·2
52·2	65·4	71·5	75·4	46·0	55·6
52·3	66·0	71·8	75·7	49·2	57·6
62·0	66·2	72·1	79·4	49·4	58·0
62·3	66·4	72·2		49·4	58·9
63·2	67·8	72·5		51·3	60·3
average : 65·95				average : 51·31	

14·6 mm difference in the average size of these specimens, *M. nitidulum* being the larger. The largest specimen of *M. nitidulum* is 19·1 mm larger than the largest *M. affine*. Fig. 3 also indicates a lack of *M. affine* in the larger size range.

That this is not due to insufficient material is shown by the relative size at which the luminous scales of the caudal peduncle are developed. These scales are believed to indicate maturity in at least certain species of Myctophidae. Although I have not checked sex internally, I presume, as others have previously, that those specimens

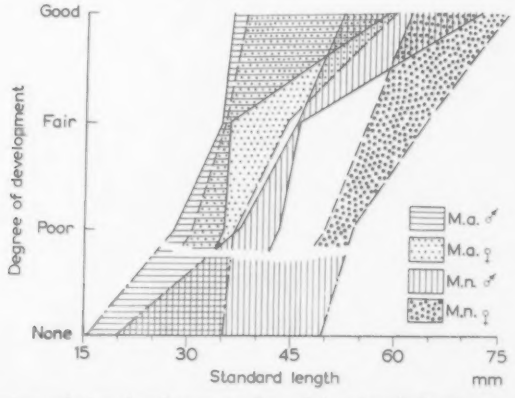

Fig. 4. Diagram showing relative development of caudal-peduncle luminous scales in *Myctophum affine* and *M. nitidulum*. There is very little overlap either between the species or between males or females. The region of undeveloped scales is indicated by the male symbol for each species, although the sex of these specimens was undetermined.

possessing dorsal luminous scales on the caudal peduncle are males, those having ventral ones, females. In the species under consideration, males of *M. affine* usually have seven or eight such scales, males of *M. nitidulum* six or seven, seven being the mode in each. Female *M. affine* usually have three luminous ventral scales, *M. nitidulum* three or four. (One large specimen of *M. nitidulum* from the Gulf of Mexico had both dorsal and ventral luminous scales).

The relative size at which these luminous scales are developed is shown in Fig. 4. The degrees of development used are arbitrary, but are believed to represent the observations satisfactorily.

In both species, the luminous scales of the male develop at a smaller size than those of the female. Between males, there is little overlap in size at any given degree of development of these scales. The smallest male *M. affine* to show luminous scale development is 9·3 mm smaller than the similar *M. nitidulum*. The largest *M. affine* with well-developed luminous scales is 59·0 mm, the smallest *M. nitidulum* 52·2 mm.

The difference between females is even more striking. The smallest female *M. affine* to show luminous-scale development is 30·4 mm, the smallest *M. nitidulum* 48·2 mm. There is no overlap between *M. nitidulum* and *M. affine* females with well-developed luminous scales.

The difference in the size at which the luminous scales are developed, therefore, supports the conclusion that *Myctophum affine* is a smaller fish than *M. nitidulum*. Even considering species regardless of sex, Fig. 4 indicates very little overlap in size at all between specimens of each degree of development.

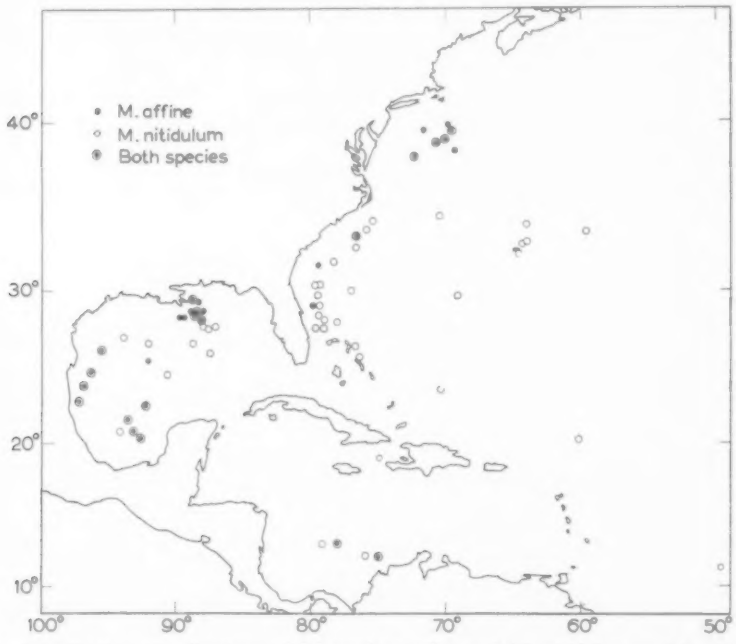

Fig. 5. Distribution of collections of *Myctophum affine* and *M. nitidulum* used in this study.

GEOGRAPHIC VARIATION AND DISTRIBUTION IN THE WESTERN NORTH ATLANTIC

From the collections at hand, there is no convincing evidence of any difference in distribution of the two species. They have both been taken in the western Atlantic proper, the Gulf of Mexico, and the Caribbean Sea, and they have often been taken together in each of these regions (Fig. 5). At twenty-three out of seventy-six collecting stations, the two were both present.

Breakdown of the meristic data for each species into the three regions is shown in Tables 3 and 4. Too few specimens are available from the Caribbean to justify any conclusions. In the Atlantic and Gulf samples of *M. affine*, there is a slight modal difference in number of AO photophores, which is the only character suggesting distinctiveness of the two populations. In *M. nitidulum* there is a notable difference in number of lateral-line scales, and less-trenchant modal differences in numbers of pectoral rays and gill rakers. This data seems to indicate that Gulf and Atlantic populations of *M. nitidulum* are more effectively isolated than those of *M. affine*, but that gene flow is not greatly restricted in either species between the two areas.

Table 3. *Frequency distributions of meristic characters of* Myctophum affine *from different geographical areas*

	Dorsal rays				*Anal rays*				*Pectoral rays*			
	9	10	11	$\bar{x}$	16	17	18	$\bar{x}$	12	13	14	$\bar{x}$
Atlantic	3	35	2	10·0	5	31	4	17·0	6	37	37	13·4
Gulf	1	46	5	10·1	8	34	10	17·0	10	74	15	13·1
Caribbean	—	3	—	10·0	1	2	—	16·7	—	2	4	13·7

	AOa			*AOp*				*Total AO*				
	8	9	$\bar{x}$	4	5	6	$\bar{x}$	12	13	14	15	$\bar{x}$
Atlantic	21	19	8·5	7	27	6	5·0	2	21	14	3	13·5
Gulf	24	28	8·5	2	37	13	5·2	—	17	31	4	13·8
Caribbean	2	1	8.3	—	—	3	6·0	—	—	2	1	14·3

	Lateral-line scales							*Upper rakers*			
	36	37	38	39	40	41	$\bar{x}$	5	6	7	$\bar{x}$
Atlantic	1	1	8	21	8	1	38·9	3	28	9	6.2
Gulf	—	4	12	20	14	1	38·7	5	43	4	6·0
Caribbean	—	—	3	—	—	—	38·0	1	2	—	5·7

	Lower rakers						*Total rakers*						
	13	14	15	16	17	$\bar{x}$	19	20	21	22	23	24	$\bar{x}$
Atlantic	—	6	23	10	1	15·2	2	4	16	13	5	—	21·4
Gulf	1	9	30	10	2	15·5	3	8	27	—	—	1	21·0
Caribbean	1	1	—	1	—	14·3	2	—	—	1	—	—	20·0

It is interesting to speculate about the mechanisms for reproductive isolation in these two species. The photophore and luminous scale patterns would seem to be the logical species-specific recognition characters, but these are almost identical in *M. affine* and *M. nitidulum*. Since all the collections used in this study were made at the surface, there is no suggestion of a possible difference in depth at which spawning might take place ; nor do published references help, as they do not distinguish between the two species. It may be that lack of interbreeding is due to physiological mechanisms, which must have developed during a former isolation. The similarity of the present ranges of these species gives no hint of such a past separation. It is possible, though improbable, that the similarities of these two forms are due to convergence, and that

they are members of different phylogenetic groups. The present state of Myctophid systematics does not permit an answer to this.

Table 4. *Frequency distributions of meristic characters of* Myctophum nitidulum *from different geographical areas*

	Dorsal rays				*Anal rays*					*Pectoral rays*					
	9	10	11	$\bar{x}$	16	17	18	19	$\bar{x}$	11	12	13	14	15	$\bar{x}$
Atlantic	—	29	2	10·1	—	11	15	5	17·8	—	3	22	31	4	13·6
Gulf	—	27	4	10·1	1	9	20	1	17·7	—	8	33	19	2	13·3
Caribbean	1	7	—	9·8	—	6	2	—	17·3						

	AOa					*AOp*				*Total AO*					
	7	8	9	10	$\bar{x}$	4	5	6	$\bar{x}$	12	13	14	15	16	$\bar{x}$
Atlantic	1	4	22	4	8·9	5	21	5	5·0	1	6	19	4	1	13·9
Gulf	—	8	22	1	8·8	3	20	8	5·1	—	8	17	6	—	13·9
Caribbean	—	4	3	1	8·6	—	6	2	5·3	—	2	5	1	—	13·9

	Lateral-line scales							*Upper rakers*				
	36	37	38	39	40	41	$\bar{x}$	4	5	6	7	$\bar{x}$
Atlantic	1	4	18	7	1	—	38·1	—	26	4	1	5·2
Gulf	—	—	7	13	11	—	39·1	1	23	7	—	5·2
Caribbean	—	—	4	2	—	1	38·7	—	6	1	—	5·1

	Lower rakers				*Total raker:*				
	13	14	15	$\bar{x}$	18	19	20	21	$\bar{x}$
Atlantic	15	14	2	13·6	12	14	4	1	18·8
Gulf	5	15	11	14·2	6	13	6	6	19·4
Caribbean	—	4	3	14·4	—	4	2	1	19·6

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Woods Hole Oceanographic Institute
Woods Hole, Mass., U.S.A.

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Profiles across the Peru–Chile Trench

J. M. ZEIGLER, W. D. ATHEARN and H. SMALL

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Abstract—Three general types of profile across the Peru–Chile Trench are shown : trench with gently basined topography, trench with smooth flattish floor, and trench with abrupt topography. Differences in trench shape are ascribed to differences in agents and rates of sedimentation.

Production of plankton whose skeletons might accumulate as bottom sediment is reasonably uniform along the length of the area examined, therefore differences in sedimentation must be associated with available supply from the South American continent. Presumably the supply would be greater north of the Chilean desert because more streams reach the sea and in some places, such as near Talara, Peru, the coastal sediments are less resistant than the volcanics along much of the Chilean coast.

If the trench is not the same age throughout its length, then the arguments for different sedimentary environments do not necessarily explain differences in bottom topography, nor from profiles alone is it possible to say which end of the trench is younger ; however a progressively growing earth flexture must then be assumed.

Topographic features such as subsidiary trenches to the side of the main trench, grabens and horsts, and submarine canyons are described.

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INTRODUCTION

THE deep, narrow trench whose trend closely parallels the western coast of South America from Ecuador to Chile is a submarine feature of great interest. This trench in its entirety will be referred to as the Peru-Chile Trench (see FISHER and REVELLE, 1955). The Woods Hole Oceanographic Institution's research vessel *Atlantis*, under the leadership of the late H. C. STETSON and P. D. TRASK, occupied 100 coring stations off the coasts of Peru and northern Chile during November and December, 1955 for the purpose of investigating sediments of this trench. The track of the vessel and positions of coring stations are shown in Fig. 1.

PREVIOUS WORK

Insofar as we can ascertain, first knowledge of these deep areas dates back 80 or 90 years. Submarine telegraph cables were laid as early as 1875 along parts of the west coast of South America (MILNE, 1897, pp. 266–267); and it is likely that cable ships first discovered the deeps. The cable ship *Relay* of the Central and South American Cable Company reported a wire sounding of 4175 fathoms (7635 m) in the Richards Deep off Taltal, Chile, in 1890 (BENCKER, 1930). Deep soundings given in the same report for the Haeckel Deep (approximately 32°S) and for the Krümmel Deep (approximately 18°S) probably were taken by cable ships also. The deepest sounding reported prior to the " Shellback " expedition for the MILNE-EDWARDS Deep off Callao (approximately 12°S) was taken by the U.S.S. *Alaska* in 1881.

The " Shellback " expedition of 1952 carried out by the research vessel *Horizon* made several crossings of the trench between the latitudes of Guayaquil, Ecuador, and Callao, Peru, and the *Atlantis* cruise of 1955 made several crossings between

the latitudes of Talara, Peru, and 25°S (about 75 miles south of Antofagasta, Chile). These are the only two scientific expeditions ever to undertake anything like a systematic exploration of the trench. Other research ships which made occasional crossings and some soundings did so principally to reach ports in the area. These include the Italian *Vettor Pisani* in 1884, the U.S. Fish Commission Steamer *Albatross* in 1904, and the non-magnetic ship *Carnegie* in 1929.

The first charts to show deep areas along the west coast of South America were published by Sir JOHN MURRAY in 1895 along with his summary of the scientific results of the *Challenger* expedition (THOMPSON and MURRAY, 1895). These charts were the result of plotting and contouring of all available soundings deeper than 1000 fathoms (1830 m). Areas deeper than 3000 fathoms (5500 m) were called deeps and were given distinctive names (MURRAY, 1899). Thus it appears that MURRAY not only first charted the deeps of the Peru–Chile Trench but also named them. From north to south these were (1) Milne–Edwards Deep, a nearly circular area north-west of Callao; (2) Krümmel Deep, a circular area off Arica, Peru; (3) Richards Deep, an elongated area extending from 19·5°S to 28°S off northern Chile ; and (4) Haeckel Deep, a small elongated area north-west of Valparaiso. Four years later a slightly revised chart was published along with a review of existing knowledge of ocean bottom conditions (MURRAY, 1899). Contours of Milne–Edwards Deep, Krümmel Deep, and Haeckel Deep remained about the same, but Richards Deep of the 1895 chart was divided into two deeps with a shallower " saddle " between. The name Richards Deep was retained for the more southerly area between 23°S and 26°S while the more northerly area between 19°S and 21°S was named Bartholomew Deep. Thirteen years later, in their book *The Depths of the Ocean* MURRAY and HJORT (1912) reproduced this 1899 chart in essentially its original form.

Available bathymetric charts of the area produced since the advent of echo sounding portray the trench and its deeps in about the same form and position as given by MURRAY's charts. Most notable of these is the *General Bathymetric Chart of the Oceans*, published by the INTERNATIONAL HYDROGRAPHIC BUREAU of Monaco. The most recent edition of the sheet covering the southern Atlantic and south-eastern Pacific Oceans (Sheet A'_1) was published in 1936. The Geologic Map of South America, published in 1950 by the Geological Society of America, also includes contours of the Peru–Chile Trench, but does not show soundings upon which the contours were based. Another recent set of charts showing the trench and its deep areas was published in a paper dealing principally with the submarine configuration off Callao and Lima by SCHWEIGGER (1947). It is interesting to note that SCHWEIGGER, who based his contours on soundings from charts of the U.S. Hydrographic Office and of the Peruvian Hydrographic Service, neglected earlier names for the deeps and applied new names to two, leaving the others unnamed. Those renamed are Fosa de Lima (Milne–Edwards Deep) and Fosa de Arica (Krümmel Deep).

It is clear from a perusal of data presented on the more recent charts that a great deal more surveying needs to be done before the exact shape of the Peru–Chile Trench can be determined. Profiles resulting from the " Shellback " and *Atlantis* expeditions are steps in accomplishing this work.

INSTRUMENTS AND NAVIGATION

Echo sounding data, obtained in conjunction with the coring programme, are

presented as a series of profiles across the trench. The sounding equipment used consists of an EDO echo sounder and transducer and a variable-speed, precision-powered, correlation recorder developed at the Woods Hole Oceanographic Institution. The records are produced on Alfax type A, 19 in. wide, damp chemical paper. Instrumentation is described in detail by KNOTT and HERSEY (1956).

Because no modern navigational aids such as Loran or other radio-time location systems are available off the western coast of South America, navigational controls used by the *Atlantis* depended upon various types of astronomic fixes, occasional land bearings, and dead reckoning. Almost continuously overcast weather made star fixes rare, and strong surface currents occasionally caused the ship to be set in unpredictable ways. The ship's pitometer log, designed to register distance travelled through water and the continuous course recorder which is coupled with the gyrocompass and plots changes in the ship's heading against time, were especially useful in navigation.

Particular care was taken to plot the ship's track as accurately as possible, especially where bottom profiles were to be constructed. Inaccuracies in plotting distance could cause distortion of slopes shown in profiles, particularly in areas of much relief. It was found after a number of comparisons that distance travelled between known positions (such as those determined by land bearings when the ship was near the coast) was consistently about 1·1 times that registered by the pitometer log. This factor was used generally between dead-reckoning positions. Each track has also been adjusted as well as possible for current set.

Inasmuch as some profiles can be constructed more accurately than others, the type of positional control is indicated along each leg of cruise track. Five types of fixes are differentiated on the cruise plot (Fig. 1) and on each of the *Atlantis* profiles. In decreasing order of reliability these are : (1) Land-bearing fixes ; (2) Star fixes ; (3) Local apparent noon sun lines, abbreviated L.A.N. ; (4) Sun lines ; and (5) Dead-reckoning positions.

Because some navigational uncertainty could not be eliminated, particularly at deep coring stations, profiles as drawn show breaks of an arbitrary but consistent width at the station. Breaks near the westerly end of profile NN′ (Fig. 5) result, however, from obscurities in the echogram which could not be resolved and not from stops at stations. It will be noted that sometimes the ship appeared to drift back on its track. At other times the ship drifted ahead (see Station 76, Profile QQ′, Fig. 5). Usually this backward or forward drift at stations had a sidewise component. Therefore, those profiles along which there are coring stations should properly be considered as a series of short, broken profiles lying not entirely in a straight line.

All depths given in the text and figures are based on a velocity of sound in water of 4800 ft/sec. To obtain a closer approximation of true depths at specific locations, corrections based on the average sound velocity in the water from surface to bottom must be applied.. MATTHEWS (1939) has published tables of such corrections for all ocean areas. These corrections cannot be assumed to be absolutely accurate, but will generally give more nearly true soundings than uncorrected values, particularly in very deep water where the positive correction becomes in the order of 4 per cent. For example, using MATTHEWS' tables to correct the deepest *Atlantis* sounding which was 4180 fathoms (7645 m), a corrected value of 4360 fathoms (7975 m) is obtained. Corrections based on MATTHEWS' tables have been applied to Profile

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MM′ (Fig. 5). Here the exaggerated profile consists of two lines ; the upper is the profile interpreted from the echogram, while the lower is the corrected profile. In deeper parts of the trench corrections are considerable.

Unfortunately echo sounders record the closest bottom first, whether that bottom is in front of, behind, or to the side of the vessel. In some areas of rough bottom several echoes are recorded at different depths for the same position of the ship. The problem of deciding what the true depth is and how to correct bottom slope can be somewhat resolved either analytically or graphically. An excellent treatment of analytical slope corrections and the distortion of topographic shapes produced by the echo sounder was given by DE VANSSAY DE BLAVOUS (1930 ; 1933). His work is the more remarkable in that it was written in the early days of echo sounding with equipment in mind that would give only spot soundings rather than a continuous record of soundings and would time only the first echo arrival rather than resolve multiple echo surfaces. However, his analyses can well be extended to apply to records from modern high-resolution echo sounders. The usual method for graphical slope corrections, swinging arcs with the apparent soundings as radii and fitting a curve tangent to these to represent the true bottom surface, has been described by MURRAY (1941). Slope corrections were made by the graphical method to part of profile MM′ landward of the trench bottom and the comparison between apparent bottom type and corrected bottom shape may be seen in Fig. 2. When topography

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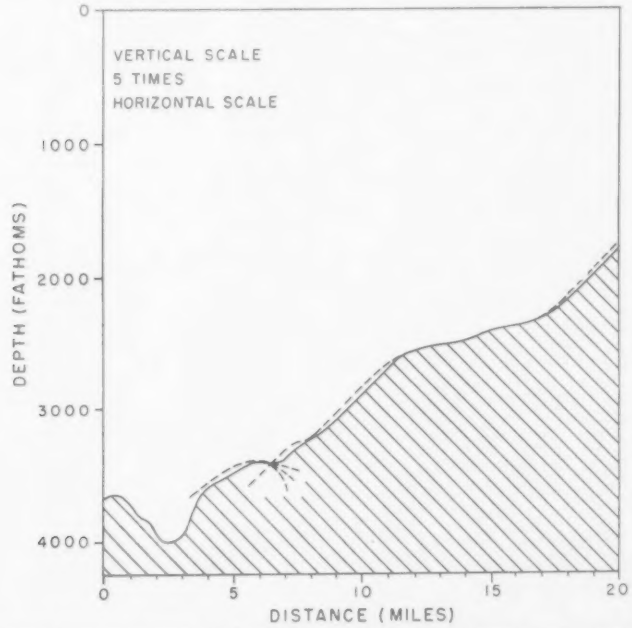

Fig. 2. Comparison between recorded depth (dotted line) and adjusted depth (solid line) for part of Profile MM′.

is rough, as was usual on the western or seaward side of the trench, slope corrections are too time-consuming and about all one can do is to plot the highest and lowest points of the features shown on echograms and estimate slopes in between. For

rigorous application of slope corrections, the sounding profile must be normal to the contour lines and it must be assumed that the echo path from ship to bottom is normal to the tangent of the bottom surface at the point of reflection. Except for the example cited, slope corrections were omitted or only estimated in preparing these profiles.

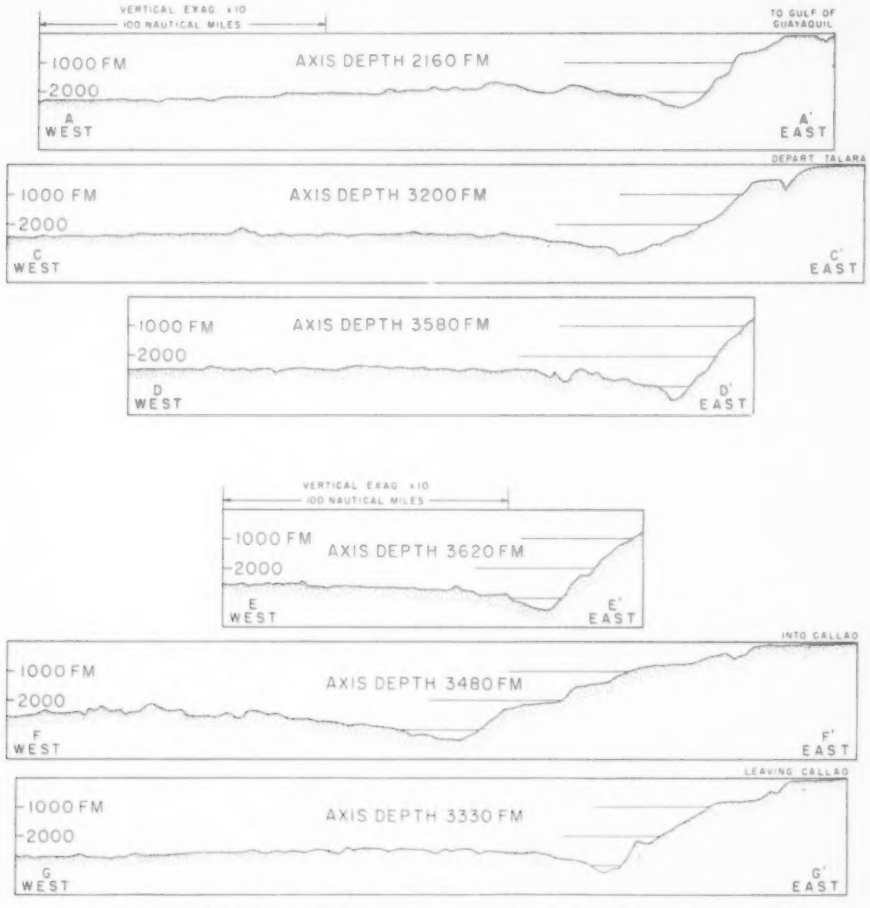

Fig. 3. "Shellback" profiles between Talara and Callao, Peru (AA′ to GG′).

DESCRIPTION

Each *Atlantis* traverse more or less normal to the coast, crossed a trench and although there were gaps up to 120 miles wide between some traverses, it is probable that the Peru–Chile Trench is continuous between northern Peru and north central Chile. SHUMWAY (1957) reports the trench as far north as Ecuador, between Carnegie Ridge and the South American continent, and this trench is contoured on the Geologic Map of South America (STOSE, 1950) to 36°S lat. almost to Conception, Chile.

The deepest uncorrected echo sounding obtained by the *Atlantis* (4180 fathoms [7645 m]) was located about 40 miles west of Antofagasta, Chile, on Profile PP′

(Fig. 5). The trench becomes shallower to the north and is only 2000 fathoms (4750 m) deep off Talara, Peru (Profile AA′, Fig. 3). The 3000 fathom contour (5500 m) is not continuous for the full length of the trench, but encloses two narrow strips with a somewhat shallower " saddle " between them. The *Atlantis* crossed this " saddle " at 15·4°S, 76·3°W (Profile JJ′, Fig. 4) obtaining a depth of approximately 2600 fathoms (4750 m), which even here is almost 900 fathoms (1645 m) deeper than the sea floor on the seaward side of the trench.

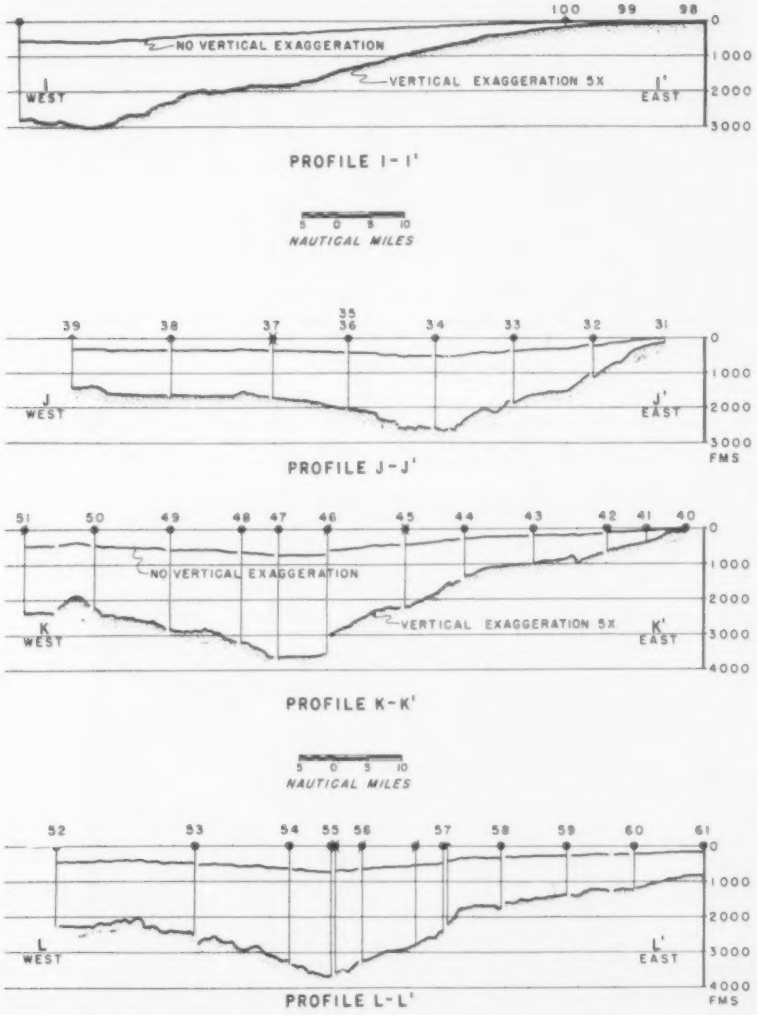

Fig. 4. *Atlantis* profiles between Chincha Islands, Peru and Punta Madrid, Chile (II′ to LL′).

Cross-sections of bottom topography across the Peru–Chile Trench may be classed as three general types. In the first, along the north and central Peruvian coast from Talara to the Chincha Islands (Profiles AA through II′), the relief is not great and the trench appears broad and only gently basined. It should be noted that the northern

sections shown in Fig. 3 (Profiles AA′ through GG′) are "Shellback" profiles and have a vertical exaggeration of ten times the horizontal scale and therefore the cross-sections of the trench appear somewhat sharper than they do at five to one exaggeration used in Figs. 4 and 5. In the second category are cross-sections with smooth,

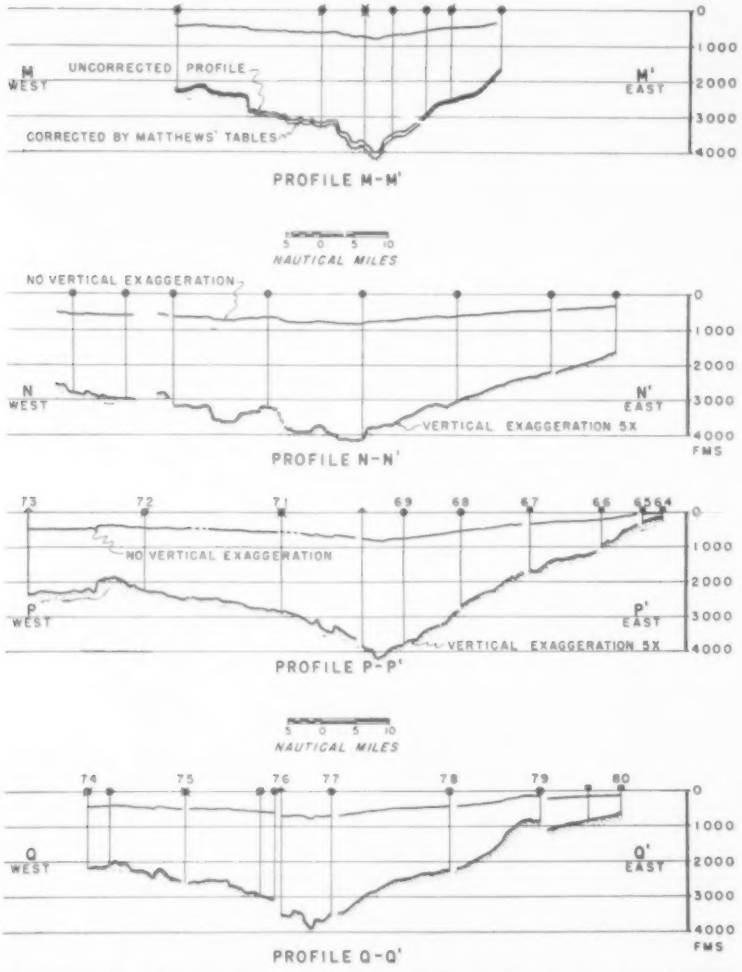

Fig. 5. *Atlantis* profiles between Punta Guanillo and Punta Posallaves, Chile (MM′ to QQ′).

flattish bottoms (Fig. 6) located in the bend of the South American coast off southern Peru and northern Chile (Profiles KK′ and LL′). Unfortunately the profiles are so reduced in scale that many of these smooth bottoms do not show, but they are strikingly apparent on the echograms. In the third category are cross-sections with narrower, sharper axes and pronounced bottom roughness. They are the southernmost profiles MM′, PP′, QQ′ and JJ′.

Generally the roughest terrain is found immediately seaward of the trench axis. This is particularly noticeable in profiles off southern Peru and northern Chile.

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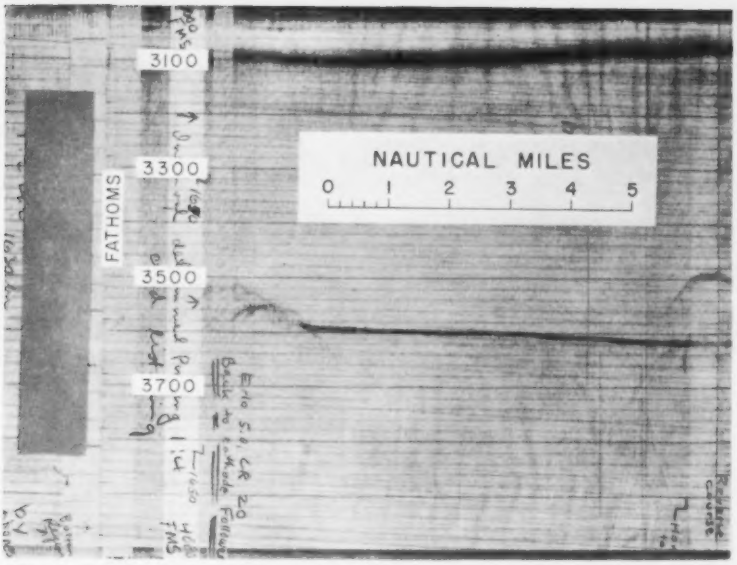

Fig. 6. Smooth bottom characteristics of some portions of Peru–Chile Trench.

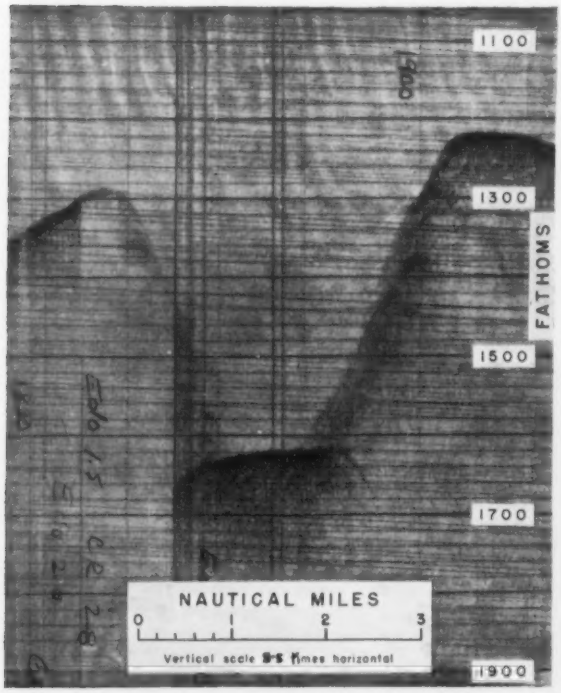

Fig. 7. Echogram of canyon 30 miles south south-west of Pescadores Point, Peru.

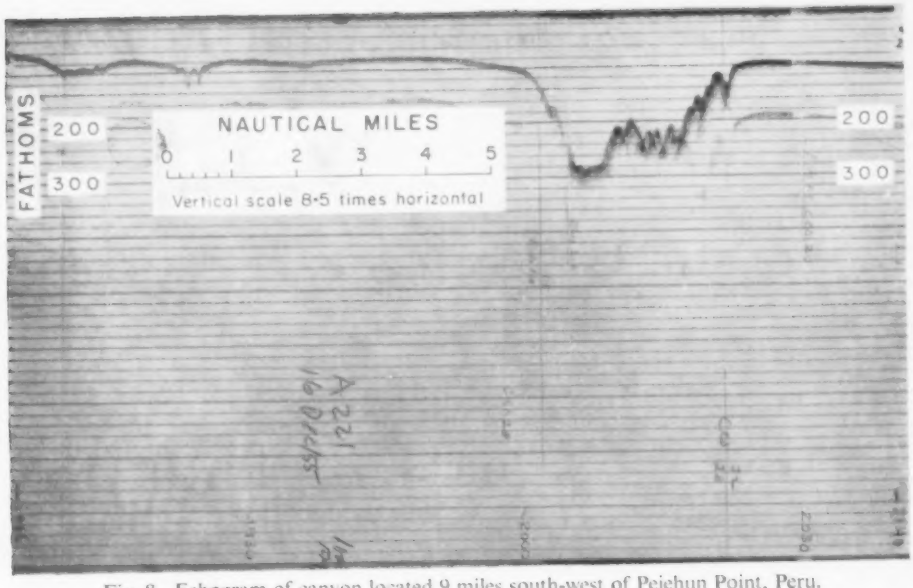

Fig. 8. Echogram of canyon located 9 miles south-west of Pejehun Point, Peru.

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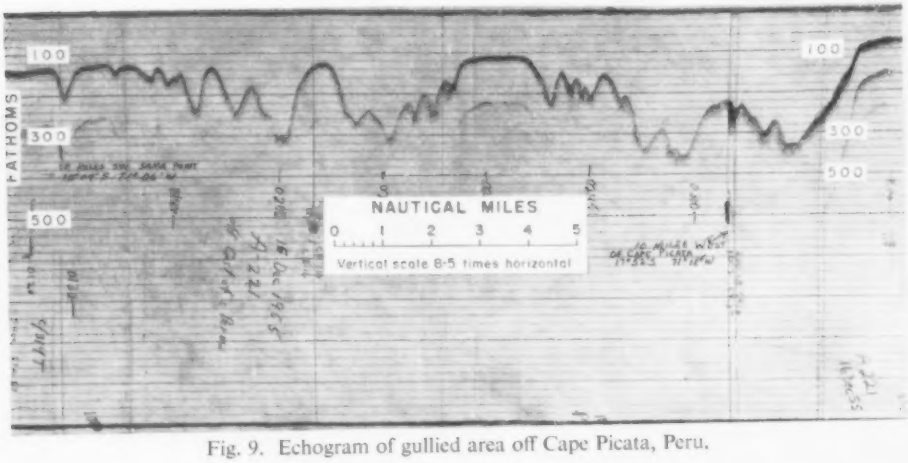

Fig. 9. Echogram of gullied area off Cape Picata, Peru.

More intense tectonic activity seaward of the axis may have produced this effect, but it seems more likely that heavier sedimentation on the landward side has subdued equally rough topography. Indeed, occasional strong features do appear to protrude through the sediment blanket, or at least interrupt the smoother profile attributed to the sedimentary blanket (see Profiles GG′, JJ′ and LL′). Notches near the landward ends of Profiles CC′ and KK′ are interpreted as more or less oblique sections of small canyons crossing the continental terrace. Occasional scarps such as those found in Profile MM′ (Fig. 5) seaward of the trench axis have up to 2400 feet (730 m) of relief and attain a slope angle approaching 45°.

CANYONS

There are two general areas of canyons and gullies along the Peruvian coast. Ones lies between the Peru-Chile boundary on the south (about 18° 20′S lat.) and Paracas Peninsula at about 14°S on the north (see canyon and gully notation in Fig. 1). The second area lies along the coast of northern Peru between Cabo Illesca (6°S lat.) on the south and the Gulf of Guayaquil on the north.

The *Atlantis* crossed what appears to be the most significant canyon in the southerly area at 16° 49′S lat., 73° 32′W long. (about 30 miles south south-westward of Pescadores Point, Peru) on her southward voyage (Fig. 7) and attempted to locate the shoreward end of this canyon on the homeward leg of the cruise. A canyon was crossed 20 miles northeast of that position at 16° 35′S, 73° 20′W. Although it cannot be stated definitely that this was the same canyon, an axial line drawn between both positions does run perpendicular to the trend of the continental slope.

If these two profiles do represent different sections of one single canyon, its size is comparable to those on the continental slope of the eastern United States (e.g. Oceanographer or Lydonia Canyon off Georges Bank). Echograms of the seaward traverse made on the southward leg show 2100–2400 ft (640–730 m) of relief, with a rim-to-rim width of 3¼ miles and a bottom width of 1½ miles (Fig. 7). Echograms of the landward crossing made on the homeward leg of the cruise show a maximum relief of 2750 ft (840 m), with a rim-to-rim width of 4 miles and a bottom width of ½ mile.

Other small canyons and gullies occur along this part of the Peruvian coast. A shallower canyon (Fig. 8) was crossed 9 miles offshore from Pejehun Point, or about 20 miles south-eastward from the larger canyon discussed above. Here maximum relief is about 1100 ft (335 m) with a rim-to-rim distance of about 3¼ miles. Further investigation might show this to develop seaward into a somewhat larger canyon than is indicated from the single profile obtained by the *Atlantis*. About 10 miles seaward of Cape Picata, 60 miles north-westward from the Peru-Chile border, is a series of gullies (Fig. 9) whose profiles have a vertical depth range of approximately 600 ft (180 m). Some of these gullies seem to be a seaward extension of sub-aerial drainage lines. In several other locations along the coast between Cape Picata and Paracas Peninsula such gullies were observed, but their seaward development is not known.

Although a little attention has been given to the canyons and gullies of this area by submarine geologists (HESS and MACCLINTOCK, 1936 ; SHEPARD and BEARD, 1938 ; SHEPARD, 1948), submarine cable companies have been well aware of their existence since the 1870s. Sediment movements of one sort or another in these

gullies were responsible for frequent dislocation and rupture of the coastal cables, particularly off Mollendo (17°S, 72°W) and off Pescadores Point, until the early 1890s when the cables were moved shoreward of the gullyheads.* This was the necessary remedy and the companies were no longer plagued by the frequent breaks (BENEST, 1899).

There is little doubt that the larger canyon discussed above was well known to cable companies and probably much information concerning it remains in company files, but the present writers know of no detailed discussion of it in the literature.

Canyons and gullies in the northerly area were not investigated by *Atlantis* geologists but their existence was recorded by the echo sounder as the ship approached Talara, Peru, from the south. The whole section of echogram running due north from a point 15 miles off Punta Negra to the continental shelf just south of Punta Parinas is interrupted by gullies. These were of about the same dimensions as those found in the Cape Picata and Pejehun Point area (cf. Figs. 8 and 9). One of the largest, as might be expected, was just seaward of the mouth of the Rio Chira, north of Paita. Gullies and cable breaks in this general area are also discussed briefly by BENEST.

DISCUSSION

The three general types of cross-sections across the trench, each restricted to its own particular area, may reflect variations in the sedimentary environment or possibly a difference in age between separate areas. Sharp, V-shaped profiles located off northern and north-central Chile suggest a young trench in which relatively little sedimentation has yet occurred. It does not follow, however, that the broader, shallower sections off northern Peru are older features partly filled by large accumulations of sediment. The broader sections may indicate the early stages of a trench which is evolving a greater relief. Consequently our data cannot properly support assumptions concerning the relative age of portions of the trench. It is possible that the trench is the same age throughout its length but that rates of sedimentation are different along different portions of the South American coast under study. There are many more rivers reaching the sea between Arica in northern Chile and Talara, Peru, than between Arica and Caldera on the desert coast which is crossed only by the Loa River. Summer rain falls at progressively lower altitudes on the mountain slopes from Chile to northern Peru until in northernmost Peru at Tumbez some rain falls on the coast (MURPHY, 1936, p. 98). Where greater volumes of water reach the sea, more sediment may reach the Peruvian trench. Thus the more gently basined parts of the trench may reflect a greater supply of sediment from the continent than the sharp, V-shaped profiles.

Variations in resistance of rocks to coastal erosion might also influence sedimentation rates. Some of the volcanics are much more resistant to erosion than sedimentary strata. The volcanics near Antofagasta, Chile, and much of the adjacent coast offer more resistance to wear than do the softer sediments near Talara, Peru.

No differences in productivity of plants and animals in the waters off the coast are established which might explain lack of topography in one portion of the trench and not in another. As a matter of fact, MURPHY (1936, pp. 263, 267) stresses the uniformity of the biota and the physical characteristics which control it along the coast between Antofagasta, Chile, and Paita, Peru.

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The writers believe turbidity currents to be the principal agents of sedimentation in the smooth-bottomed portions of the Peru-Chile Trench. Canyons and gullies cutting the continental slope in this area offer numerous channels for localized turbidity flows which may have originated at the gully heads as a result of spring floods or seismic activity. BENEST (1899) observed that submarine cable breaks off Pescadores Point and Mollendo, mentioned previously, occurred during the season of heavy rains in the Arequipa district directly inland. He cites instances when the ends of broken cables were recovered entangled with boles and branches of olive trees found growing not closer than 80 miles from the coast. Intermittent streams carried flood debris to lagoons behind the beach, but as no debris was found on the seaward side of the beach BENEST suggested that underground rivers head under the lagoons and discharge large quantities of debris underwater at the gully heads. MILNE (1897) discussed seismic activity as a possible cause of " landslides " in the gullies. ERICSON, EWING and HEEZEN (1952) and NORTHRUP (1954) consider that the flat bottom of the Puerto Rico Trough resulted from deposition of large quantities of shallow-water sediments by turbidity currents. Graded bedding and high calcium carbonate content found in cores from the deep, flat floor of the trough support their view. MENARD (1955), BRUUN and KIILERICH (1955) and RAITT, FISHER and MASON (1955) suggest rapid deposition by turbidity currents to have been operative in Pacific trenches. There are many small gullies between Punta Negra and Talara, Peru, and yet the trench opposite those places is not flat bottom in the sense under discussion. The presence of canyons and gullies on slopes adjacent to trenches does not in itself mean that sufficient material will move down the canyons to form flat bottoms in the trenches. Why one area should have flattish bottoms and another not, is still not clear to us.

Smooth-bottom depressions in conjunction with side topography (Profile NN′) present an interesting puzzle. The flattish areas in question are on the seaward side of the main trench axis. Either they form the floor of side trenches subsidiary to the main trench or perhaps they form floor of submarine canyons entering the main trench from the seaward side. These two smooth-floored depressions are successively shoaler than the main trench axis, the first by approximately 150 fathoms and the second by 500 fathoms. A smooth-topped divide separates the two depressions. The profile shape of this portion of the trench is most suggestive of graben and horst topography.

The smooth top of the divide suggests that heavy deposition is not necessary for the formation of smooth bottoms and, indeed, when we devise mechanisms for depositing sediment in these basins we are faced with difficulty. If the sediment source is the South American continent, then the material must have been transported across the deeper, main trench. If the depressions are canyons and turbidity currents originating on the continental slope, the transporting agents, the currents had to flow up hill as much as 500 fathoms before depositing its load in the upper canyon. We are not accustomed to thinking that turbidity currents originate seaward from sites of deposition.

In conclusion the writers recognize that the bathymetric data from the *Atlantis* cruise have presented more problems than answers regarding the interpretation of the features of the Peru–Chile Trench. It is hoped that this paper may serve as a guide to further investigations in the area.

Acknowledgements—The writers wish to acknowledge the active cooperation of the governments of Chile and Peru. Lieut. JOSÉ CARVAJAL PAREJA of the Peruvian Navy shared in the work as long as he was on board. Mr. JOSÉ STUARDO of the Chilean Biological Station assisted greatly by standing regular watches and working on all phases of the coring operation. The writers owe much to their colleagues and to the officers and crew of the *Atlantis*.

The cruise would not have been possible without the liberal support from the Socony-Vacuum Laboratories, the Woods Hole Oceanographic Institution, and the Office of Naval Research.

Five profiles off northern Peru (Fig. 3), constructed from data taken on the "Shellback" expedition of the Scripps Institution of Oceanography in 1952, were kindly put at the disposal of the writers by Mr. GEORGE SHUMWAY of the Naval Electronics Laboratory at San Diego, California.

Woods Hole Oceanographic Institution, Woods Hole Massachusetts

Contribution No. 919 *from the Woods Hole Oceanographic Institution*

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Carnegie Ridge bathymetry

GEORGE SHUMWAY

(*Received* 17 *June* 1957)

INTRODUCTION

CARNEGIE Ridge is a sea floor elevation lying directly west of Ecuador, but separated from the continent by a narrow trench. Its westward extention joins the platform on which the Galapagos Islands are found through a saddle at a depth between 1200 and 1300 fm. About 7200 square nautical miles of sea floor on Carnegie Ridge lie shoaler than 800 fm. The feature is of geological interest because it lies so close to the South American continent yet is so distinctly separated from it by the trench.

The general features of Carnegie Ridge have been described previously by the writer, and some geological implications have been discussed (SHUMWAY, 1954). Since this earlier report, thousands of miles of new sounding lines have been obtained on the Research Vessels *Horizon* and *Spencer F. Baird* of the Scripps Institution of Oceanography during the "Shellback" and "Eastropic" Expeditions, and on *Atlantis* of the Woods Hole Oceanographic Institution during Cruise 221 (Fig. 1). A more detailed bathymetric chart (Fig. 2) has been constructed on the basis of this new data together with that from the U.S. Navy Expedition "Hijump" and with spot soundings from U.S.N. Hydrographic Office Charts 0823, 1176, 1177, 1798, and 5486. Nominal echo sounder depths, based on the assumption of a sound velocity in sea water of 4800 ft/sec, have been used for this chart. Some generalized coastal geology of Ecuador is included for the sake of completeness (LEWIS, TSCHOPP and MARKS, Pl. 1 in JENKS, 1956).

Bathymetry of the trench to the south of the area of the chart (Fig. 2), i.e. off Peru and Chile, is presented in the accompanying paper by JOHN M. ZEIGLER (1957).

BATHYMETRY

Atlantis' echo sounder profile across the south-east edge of Carnegie Ridge (Fig. 1) indicates that the feature is somewhat larger than previously believed. It stands about one nautical mile above the axis of the trench to the east of it. The east slope of the elevation, which leads down into the trench, is about as steep as the continental slope on the east side of the trench axis. Within the closed 700 fm contour on top of Carnegie Ridge only three soundings are available : 700, 620, 440 fm.

An echogram recorded continuously by *Atlantis* along the shoal portion of the elevation (Fig. 3) reveals a striking change from a jagged irregular bottom to a smooth one. The rough section is along the southern edge of the elevation, and the smooth part along the eastern edge.

The rather abrupt change from irregular to smooth bottom, and the smooth bottom itself, on the top of an elevation such as this, are unusual features. In the writer's earlier discussion of Carnegie Ridge (SHUMWAY, 1954) it was speculated that the eastern end of the elevation once might have been a part of the South American

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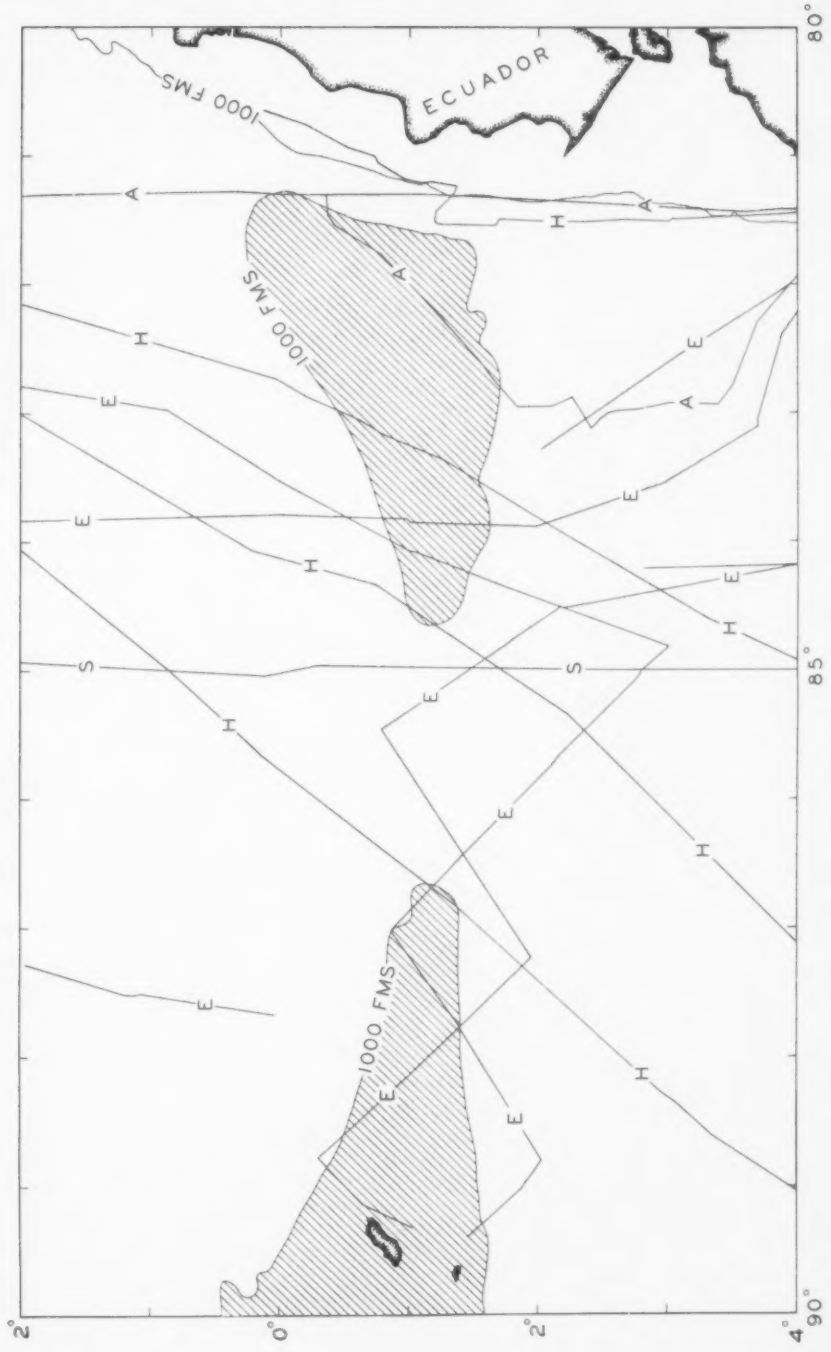

Fig. 1. Sounding lines in the Carnegie Ridge area. Letters indicate expeditions as follows: A—*Atlantis* 221; E—"Eastropic"; H—"Hijump"; S—"Shellback".

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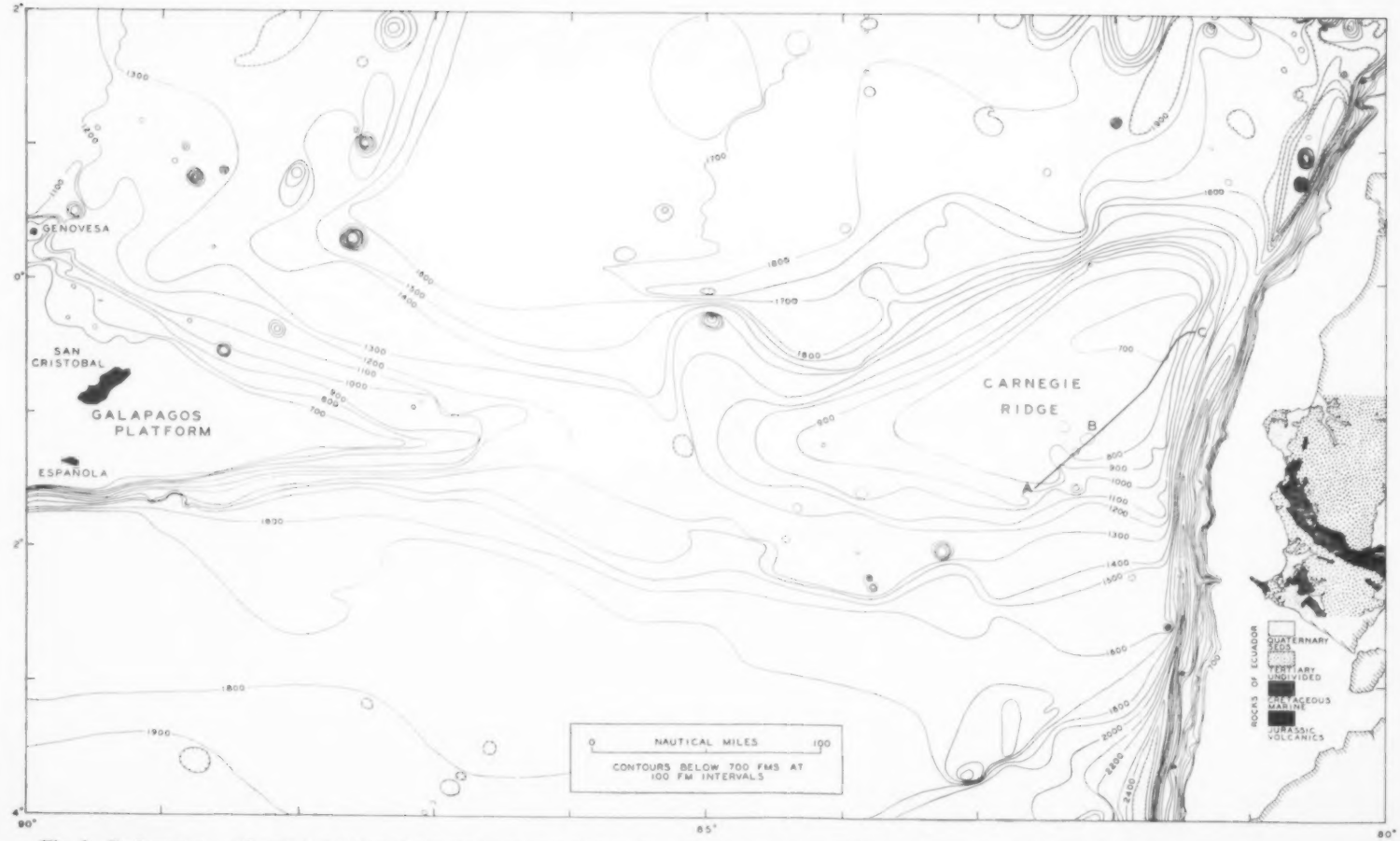

Fig. 2. Bathymetry on Carnegie Ridge and the sea floor west of Ecuador. Contours below 700 fm only, at 100 fm intervals. Geology in Ecuador after LEWIS, TSCHOPP and MARKS, Pl.1, in JENKS (1956).

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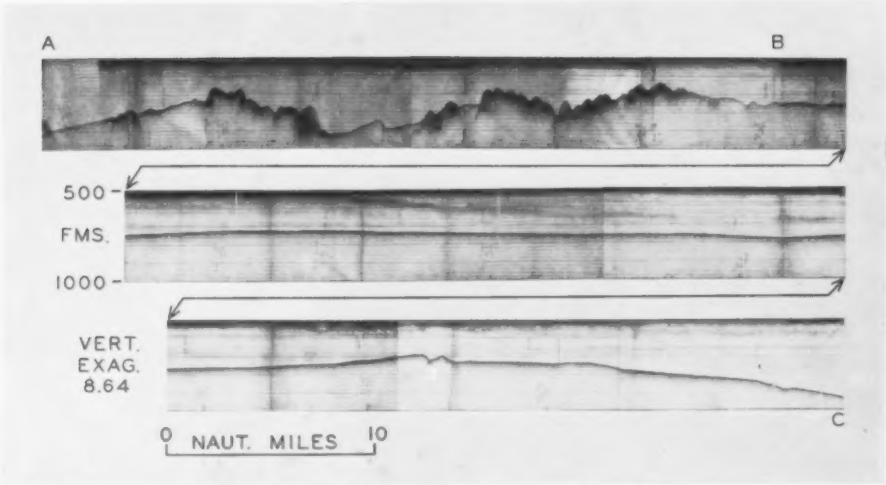

Fig. 3. Echogram along Carnegie Ridge, southeast side. Sea floor depths in fathoms. For location see line A, B, C of Fig. 2.

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Continent before the trench came into existence. In following this speculation, it might be argued that the smooth eastern portion of Carnegie Ridge is the sunken extension of the coastal lowlands of western Ecuador. On the other hand, the elevated area once may have been part of the deep-sea floor lying near the base of the continental slope west of Ecuador and is smooth because the area was originally part of the sedimentary apron at the edge of the continent. The smooth area on top of Carnegie Ridge should be a suitable place for seismic refraction studies. More significant interpretations must await the results of such studies.

The sea floor elevation from which rise the islands of the Galapagos extends eastward to join the westward extension of Carnegie Ridge (Fig. 2). Sounding lines from the "Eastropic" Expedition cross the eastern extension of this platform a number of times. They establish that an area shoaler than 1000 fm extends at least 150 nautical miles to the east of the eastern end of San Cristobal Island. The topography along these lines in general is irregular.

Acknowledgement—Dr. JOHN M. ZEIGLER of the Woods Hole Oceanographic Institution kindly allowed the writer to use the original sounding data from *Atlantis* Cruise 221 which is presented here.

U.S. Navy Electronics Laboratory
San Diego 52, *California, U.S.A.*

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Phosphatase activity by marine bacteria under hydrostatic pressure

RICHARD Y. MORITA and R. ARLINE HOWE

(*Received* 24 *June* 1957)

Abstract—*p*-nitrophenyl phosphate was employed to determine phosphatase activity of marine bacteria under hydrostatic pressure. A wide variation in phosphatase activity was shown to occur. With increased hydrostatic pressure the phosphatase activity of some marine bacteria increased, of others decreased, while in some it remained relatively constant.

INTRODUCTION

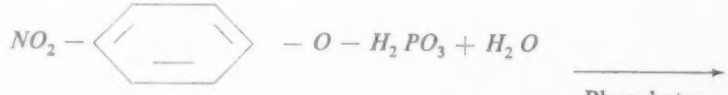
THE parameter of hydrostatic pressure in relation to the metabolic activities of organisms in the ocean has not been investigated to any great extent. However, it is known that hydrostatic pressure affects the rate of enzyme activity of whole bacterial cells (JOHNSON, EYRING and POLISSAR, 1954; MORITA, 1957). Since the regeneration of nutrients in the ocean is intimately associated with bacterial metabolism, the effect of hydrostatic pressure upon bacterial metabolism is an important factor in the overall productive capacity and fertility of the ocean.

The regeneration of phosphate in the ocean is an important factor in productivity (ZOBELL, 1946; HARVEY, 1955). Regeneration of phosphate has been shown to take place in sea-water by bacterial action (COOPER, 1935; SEIWELL and SEIWELL, 1938; WAKSMAN and CAREY, 1935; PRATT, 1950) and in marine sediments by the indigenous bacteria (MORITA, 1954; CVIIČ, 1956).

This investigation deals with the effect of hydrostatic pressure on phosphatase activity in various marine bacteria.

EXPERIMENTAL PROCEDURE

The compound, *p*-nitrophenyl phosphate (General Biochemicals, Inc.), was employed to determine the phosphatase activity (SOMMER, 1952 ; TRAMER, 1952). According to TRAMER (1952) *p*-nitrophenyl phosphate can be used to measure bacterial phosphatase accurately. This compound undergoes the following reaction when acted upon by phosphatase :



p-nitrophenyl phosphate
(colourless)

p-nitrophenol
(yellow in alkali)

p-nitrophenyl phosphate is colourless, while *p*-nitrophenol released by phosphatase produces a yellow colour in an alkaline environment. The addition of alkali not only develops the colour of the liberated *p*-nitrophenol, but also stop the enzymatic action. Every mole of *p*-nitrophenol liberated corresponds to the same amount of phosphate. Consequently, a standard curve prepared with known amounts of *p*-nitrophenol in NaOH can be used to determine the number of moles of *p*-nitrophenyl phosphate hydrolysed by the enzyme, phosphatase. The Beckman DU Spectrophotometer was used for determining the concentration of *p*-nitrophenol (450 mμ ; 1 cm cells). A blank control of buffer and substrate was used to adjust the Spectrophotometer to an optical density of zero.

The *p*-nitrophenyl phosphate used in this study was a 0·4 per cent solution which had been passed through activated charcoal to rid the solution of the *p*-nitrophenol (SIEGENTHALAR, 1956).

Cells of various marine bacteria were grown on agar plates made with medium 2216E consisting of : peptone (Difco), 5 g ; ferric phosphate, 0·01 g ; yeast extract (Difco), 1 g ; agar (Difco), 15 g ; 75 per cent aged sea-water, 1000 ml. The pH of the medium was 7·5 after autoclaving. The agar plates were inoculated with a 24 hr

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Table 1. *Micromoles of phosphate* (p-*nitrophenol*) *liberated from* p-*nitrophenyl phosphate by various marine bacteria at various hydrostatic pressures*

Culture	*Cells held at* 1 atm	*Cells held at* 200 atm	*Cells held at* 600 atm	*Cells held at* 1000 atm
	μM	*μM*	*μM*	*μM*
Bacillus borborokoites	0·058 ± 5%	0·048 ± 5%	0·076 ± 5%	0·076 ± 5%
Flavobacterium marinotypicum	2·320	3·240	2·600	1·760
Micrococcus aquivivus	0·010	0·008	0·010	0·007
Micrococcus euryhalis	0·004	0·007	0·004	0·004
Pseudomonas azotogena	0·110	0·093	0·124	0·520
Pseudomonas perfectomarinus	0·040	0·118	0·044	0·054
Pseudomonas xanthochrus	0·370	0·320	0·370	0·350
Number B13A*	0·600	0·700	0·960	1·000
Number B13B2*	2·160	2·200	3·300	3·200
Mixture**	0·053	0·034	0·034	0·033

The reaction mixture contained equal volumes of *p*-nitrophenyl phosphate, cell suspension (Klett turbidimetric reading of 450, blue filter), and M/15 phosphate buffer containing 3·5 g NaCl per 1. Incubation was for 1 hr at 30°C at various pressures. Values are the average of quadruplicate runs.

culture of the marine bacteria (listed in Table 1) which had developed in liquid (no agar) 2216E at 30°C. The inoculated agar plates were incubated at 30°C for 24 hr. Cells were harvested at the end of the incubation period and washed once with aged sea-water. The final suspension was made with M/15 phosphate buffer containing 3·5 g NaCl per litre to a turbidimetric reading of 450 on a Klett-Summerson colourimeter employing a blue filter (400–450 mμ) and a Klett tube. The colourimeter was adjusted to zero with distilled water in a Klett tube.

The reaction mixture consisted of equal volumes of suspended cells, M/15 phosphate buffer containing 3·5 g NaCl per litre, and a 0·4 per cent solution of *p*-nitrophenyl phosphate.

* Isolates from red clay. ** Indigenous bacteria from red clay.

The reaction mixture, immediately after mixing, was pipetted into small (10 x 75 mm) test tubes. The latter were filled to capacity and closed with No. 000 neoprene rubber stoppers, care being exercised to exclude air. The only oxygen present was that dissolved in the reaction mixture. The stoppered tubes were transferred immediately to pressure cylinders filled with hydraulic fluid equilibrated to 30°C. Pressure was applied for 1 hr by the procedure described by ZOBELL and OPPENHEIMER (1950). The time required to mix the reaction mixture, pipette the mixture, stopper the tubes, and pressurization, took approximately 1·5 min. The reaction mixture was incubated for 1 hr at 30°C.

After the reaction mixture had incubated for 1 hr the pressure cylinder was depressurized and the reaction mixture removed. Four millilitres of the reaction mixture was immediately added to one ml of NaOH (10 per cent, w/v) to stop the reaction. This solution was centrifuged to remove the cells and the supernatant decanted. The amount of *p*-nitrophenol was determined as described above. If the concentration of *p*-nitrophenol was too high, the sample was diluted with distilled water.

RESULTS AND DISCUSSION

Table 1 gives a comparison of the action of hydrostatic pressure on phosphatase activity of whole cells of various marine bacteria. The results indicate that bacteria studied respond differently to an increase in hydrostatic pressure. A wide variation in the amount of phosphatase activity by the various marine bacteria was noted in this study.

Most of the marine bacteria described by ZOBELL and UPHAM (1944) and used in this study, were isolated from shallow water environments. Cultures Nos. B13A and B13B2 were isolated from red clay collected during the Mid-Pacific Expedition at Station MP 38 (lat. 19°02′N, long. 177°18′W ; water depth 4712 m ; core stratum 0–5 cm). The mixture of marine bacteria consisted of the indigenous bacteria from red clay (Station MP 35-2 ; lat. 19°02′N, long. 174°58′W ; water depth 3935 m ; core stratum 333–350 cm) that were able to grow in medium 2216E (see MORITA and ZOBELL, 1955).

According to OPPENHEIMER and ZOBELL (1952) some of the bacteria used in this study when placed in sea-water broth and incubated for 8 days at 27°C gave the following results :

Multiplied at 600 atm.
Bacillus borborokoites
Micrococcus aquivivus
Pseudomonas perfectomarinus

Multiplied at 400 atm but not at 600 atm.
Flavobacterium marinotypicum

Multiplied at 1 atm but not at 200 atm.
Pseudomonas xanthochrus

Multiplied at 1 atm, but killed at 200 atm.
Micrococcus euryhalis
Pseudomonas azotogena

Of these, *M. aquivivus*, *M. euryhalis* and *Ps. xanthochrus* have shown little change in phosphatase activity at various pressures. Although *M. euryhalis* and *Ps. azotogena* were killed by prolonged incubation at 200 atm (OPPENHEIMER and ZOBELL, 1952), the enzyme system is still active for the short incubation time of the present study. *Ps. azotogena* displayed a slight drop in enzyme activity at 200 atm with subsequent increases of phosphatase activity with increased pressure.

An increase in phosphatase activity at 200 atm compared with 1 atm is noted in *F. marinotypicum* and *Ps. perfectomarinus*. However, the amount of phosphate liberated by *F. marinotypicum* decreased with further increase of pressure while in the case of *Ps. perfectomarinus* the phosphatase activity decreased at 600 atm with a slight increase in phosphatase activity at 1000 atm over that at 600 atm. Why this shift in phosphatase activity is not known.

The two cultures isolated from true pelagic sediments (Nos. B13A and B13B2) both gave increasing phosphatase activity with increased hydrostatic pressure. These organisms originally came from an environment where the hydrostatic pressure is approximately 470 atm. Since such organisms are capable of functioning under hydrostatic pressures, most of the phosphate tied up in organic matter sedimenting to the ocean bottom can be regenerated and eventually will be brought back into the food cycle again. Since pelagic sedimentation is very slow, most of the nutrients regenerated on the bottom from sedimented organic matter would not be lost. In addition, most of the dead organic matter sedimenting through the water undergoes decomposition by bacteria of one kind or another.

In the marine environment both dissolved oxygen and high hydrostatic pressure are parts of the environment under which many organisms live. Bacteria (ZOBELL and MORITA, 1957) and higher forms of animals (SPÄRCK, 1952) have been demonstrated in the deepest portions of the ocean where the hydrostatic pressure approaches 1100 atm. OPPENHEIMER and ZOBELL (1952) demonstrated that certain shallow water forms of bacteria are killed when subjected to elevated hydrostatic pressure. What actually brings about their death is not known. However, it is known that oxygen under pressure can oxidize the — SH groups (glutathione, coenzyme A, cysteine, — SH enzymes) (HAUGAARD, 1946 ; BARRON, 1955). In the present study there was dissolved oxygen in the cell suspensions, buffer and in the *p*-nitrophenyl phosphate.

The oxidation of some cellular components by oxygen under hydrostatic pressure may explain the death of some shallow water forms of bacteria such as *Ps. azotogena* and *M. euryhalis*, but does not explain the increase nor the decrease of phosphatase activity at various pressures. However, since the amount of phosphate released differs from one bacterium to another when under pressure, the factor controlling phosphatase activity of the bacterial cell under pressure is not known.

Acknowledgement—The authors wish to thank Dr. CLAUDE E. ZOBELL for the use of the Hydrostatic Pressure Apparatus.

Department of Biology
University of Houston
Houston, Texas

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The qualitative determination of some organic compounds in marine sediments

MARY A. PLUNKETT

(*Received* 1 *July* 1957)

Abstract—Four sediment samples from the Caribbean Sea were analysed qualitatively for free sugars, amino acids and simple organic acids. Two of the samples were from an anaerobic basin ; two were from aerobic areas. The sediments were extracted with hot water and 70 per cent ethanol and the residues from these extractions were hydrolysed with 6 N hydrochloric acid. The organic materials in the extracts were separated and studied qualitatively on paper chromatograms. Six free sugars, eight amino acids and seven acids were detected in one or more of the sediments analysed.

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INTRODUCTION

LITTLE is known about specific organic compounds present in marine sediments in general and particularly in those laid down under anaerobic conditions. ERDMAN, MARLETT and HANSON (1956) have reported the presence of amino acids in marine sediment hydrolysates. The work of VALLENTYNE (1954) on amino acids in lake sediments and WHITTAKER and VALLENTYNE (1957) on free sugars in lake sediment extracts together with that of ABELSON (1954, 1955), WAKSMAN and IGER (1933) and PINCK, DYAL and ALLISON (1954) demonstrates that both amino acids and sugars in certain environments are comparatively stable.

During the recent investigation of the Cariaco trench, an anaerobic basin in the Caribbean Sea (RICHARDS and VACCARO, 1956), cores were collected inside the basin and in adjacent aerobic areas. This paper reports and compares results of analyses of four of these cores for free sugars, amino acids and organic acids or their salts.

EXPERIMENTAL

Sampling. Sediments used in this study were collected at four different stations in the Caribbean Sea. The positions at which the cores were taken are given in Table 1.

Table 1. *Location of sediment samples*

Core No.	*Position*	*Length* (cm)
5	10° 37·5′N 65° 24′W	43
9	10° 46·5′N 64° 52′W	35
12	12° 36′N 58° 32′W	27
15	11° 27′N 61° 32′W	22

Cores 5 and 9 are from the Cariaco trench ; cores 12 and 15 are from outside the Cariaco trench. The cores were collected in February, 1955 with the Phleger sampler and were immediately frozen. The portions studied were cut from the centres of the frozen cores with a circular saw and were dried at a temperature of below 45°C. After drying the samples were ground to a fine powder.

Extraction. Samples (15-20 g) of each core were extracted successively with ethyl ether, hot water and 70 per cent ethanol and the residues from the extractions were finally hydrolysed by boiling with 6 N hydrochloric acid. The ethanol and acid solutions were deionized by passage through Dowex 50 cation-exchange resin. The salt free solutions were evaporated to dryness in a Rinco rotating vacuum evaporator and the residues were taken up in distilled water. The ethanol extracts were analysed for sugars and the acid hydrolysates were analysed for amino acids. The water extracts were evaporated to dryness in the same manner as the other extracts and were taken up in distilled water. The water solutions were made alkaline with NH_3 (KENNEDY and BARKER, 1951) and were analysed for organic acids. The ether extracts were saved for later study.

Qualitative paper chromatography. The one-dimensional ascending technique on Whatman No. 1 filter paper was used to resolve the organic materials present in the extracts. Positive identifications of individual compounds were obtained by comparison of R_f values using pure materials for reference and by means of specific colour reagents.

Table 2. Sugar determinations on sediment samples

Sugar	*Inside basin*		*Outside basin*	
	Core 5	*Core 9*	*Core 12*	*Core 15*
Sucrose	+	+	+	+
Glucose	+	+	+	+
Fructose	+	+	+	+
Galactose	–	+	–	+
Arabinose	+	+	–	–
Xylose	+	–	–	–

+ = detected
– = not detected

Table 3. Amino acid determinations on sediment samples

Amino acid	*Inside basin*		*Outside basin*	
	Core 5	*Core 9*	*Core 12*	*Core 15*
Leucine	+	+	+	+
Isoleucine	+	+	–	–
Glycine	+	+	+	+
Phenylalanine	+	+	+	+
Valine	+	+	+	–
Aspartic acid	+	+	+	+
Arginine	–	+	–	–
Tyrosine	–	–	–	–
Glutamic acid	–	+	–	+

+ = detected
– = not detected

Analysis of ethanol extract. An equilibrated mixture of butanol-1, acetic acid and water in the proportions of 4 : 1 : 5 v/v/v (BERSIN and MÜLLER, 1952) was used as solvent. The chromatograms were developed for varying periods up to 72 hr. Triphenyltetrazolium chloride (WALLENFELS, 1950) and benzidine (HORROCKS, 1949)

for reducing sugars and orcinol (FORSYTH, 1948) and naphthoresorcinol (PARTRIDGE, 1948) for ketoses were used as colour reagents. Results of these tests are reported in Table 2.

Analysis of acid hydrolysates. Butanol-1, acetic acid and water in the proportions 250 : 60 : 250 v/v/v (WOIWOOD, 1949) and phenol and water in the proportions 100 : 20 v/v, Mallinckrodt liquid phenol in the presence of 1 : 1 acetic acid (CONSDEN, GORDON and MARTIN, 1944), were used as solvents. Ninhydrin was used as a colour reagent to locate the amino acids. Results of these tests are reported in Table 3.

Analysis of water extract. Several organic acids or their salts were tentatively identified in the water extract. Propanol, ammonia, in the proportions of 7 : 3 v/v (ISHERWOOD and HANES, 1953) and ethanol, ammonia and water, in the proportions of 8 : 1 : 1 v/v/v (JONES, 1953) were used as solvents. Bromcresol green (LUGG and OVERELL, 1947, 1948) was used to locate the acids. Papers were also treated with ninhydrin to reveal the positions of any amino acids which might have vitiated the identification of the acids. Acids detected are listed in Table 4.

Table 4. Organic acid determinations on sediment samples

Acid	*Inside basin*		*Outside basin*	
	Core 5	*Core 9*	*Core 12*	*Core 15*
Propionic	+	+	−	−
Fumaric	+	+	−	+
Lactic	+	+	−	+
Tartaric	+	+	+	+
Citric	+	+	+	+
Oxalic	+	+	+	−
Glutaric	+	+	+	+

+ = detected
− = not detected

DISCUSSION

The information presented here indicates that the number and variety of organic materials in sediments from anaerobic basins may be greater than in sediments laid down in aerobic areas. In the cores studied the number of free sugars detected in those from the anaerobic basin was 5 for each as compared to 3 and 4 for those from the aerobic area. All of the sediments contained sucrose, glucose and fructose ; some of them contained galactose, arabinose and xylose.

The number of amino acids detected in the anaerobic basin cores was 6 and 8 as compared to 5 for each of the aerobic area cores. Leucine, glycine, phenylalanine, valine and aspartic acid were found in acid hydrolysates of each of the cores ; isoleucine, arginine and glutamic acid were detected in one or more of the hydrolysates.

Seven organic acids or their salts were found in each of the anaerobic basin cores ; 4 and 5 were found in the cores from the aerobic area. Acids detected include propionic, fumaric, lactic, tartaric, citric, oxalic and glutaric.

This data suggests a slower decomposition rate of organic matter in the sediments from the anaerobic basin or at least a greater stability of certain compounds under the conditions existing there. At the same time they support the earlier work cited (WHITTAKER and VALLENTYNE, 1957 and ERDMAN, MARLETT and HANSON, 1956) on the stability of sugars and amino acids in sediments.

This work will be continued and extended in order to show whether or not the differences noted are significant and perhaps to offer some explanation for the presence of the materials detected.

*Woods Hole Oceanographic Institution, Woods Hole, Massachusetts**
Contribution No. 924 from Woods Hole Oceanographic Institution

**Present address: Vassar College, Poughkupsie, New York*

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Determination of chlorophyll derivatives in marine sediments

WILSON L. ORR and JOHN R. GRADY

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Abstract—A rapid method is given for routine determination of acetone-soluble chlorophyll derivatives in marine sediments. The pigments are extracted from 10–100 g of wet sediment by acetone and transferred to chloroform for spectrophotometric determination. Major pigments have absorption maxima at ca. 668 mμ from which the pigment content is calculated as pheophytin *a*. Analysis requires about four hours per sample and can be carried out with a precision of about 3 per cent in sediments containing 1–100 p.p.m. of pigments.

Analysis of surface samples of basin sediments off southern California shows a range of 4–100 p.p.m. based on dry sediment. Some shallow sediments and deep sea sediments are below 1 p.p.m.

THE geochemistry of petroleum formation is a complex problem with many facets. Of the thousands of molecular structures found in crude petroleum, only a few survived the process of petroleum formation in a sufficiently unaltered condition to be recognizable as being derived from specific biochemical components of the organic matter trapped in the sediments of the source bed. The porphyrins found in petroleum are perhaps unique in this respect (DUNNING, MOORE and MYERS, 1954 ; DUNNING, MOORE and DENEKAS, 1953 ; SKINNER, 1952 ; TREIBS, 1934, 1935). They are almost certainly derived from the porphine pigments of plants and animals such as chlorophylls and hemins. Most other components of petroleum are so altered that their parent material cannot be distinguished. The optical activity of some of the high-boiling naphthenes in petroleum indicates preservation, without racemization, of portions of biochemically synthesized molecules, but the parent materials are not yet known (OAKWOOD, SHRIVER, FALL, MCALEER and WUNZ, 1952).

Very little is known about the organic matter initially buried in petroleum source beds, or when, where, and how, the conversion of plant and animal residues into petroleum takes place. Studies of organic matter in recent sediments may shed considerable light on some of these unknowns (EMERY and RITTENBERG, 1952 ; LINK, 1949 ; ORR and EMERY, 1956). The extent to which chlorophyll derivatives are preserved in various sedimentary environments is one aspect of this problem which is under investigation in this laboratory.

This paper reports a technique for the determination of the group of chlorophyll derivatives which have strong absorption bands in the red region of the spectrum and are extractable from the sediments by acetone. The technique has been used in a study of the influence of the geological environment on preservation of organic matter in sediments off the coast of southern California.

The presence of chlorophyll-like green pigments in lake and marine sediments has often been reported from spectra of alcohol or acetone extracts and the pigments have been referred to as chlorophyll, sedimentary chlorophyll, chlorophyll derivatives, or simply as green pigments (ALDERSHOFF, 1951 ; BLUMER, 1952 ; FOX, 1953 ; FOX, UPDEGRAFF and NOVELLI, 1944 ; JASTREBOVA, 1938 ; KLENOVA and JASTREBOVA,

1938 ; LUBIMENKO and RAUSER-CERNOOUSSOVA, 1930 ; VALLENTYNE, 1955). Attempts to isolate chlorophylls *a* and *b* from lake sediment by PHINNEY (1946) and from marine sediments by FOX, UPDEGRAFF and NOVELLI (1944) and by the present authors were unsuccessful. It is now generally recognized that unaltered chlorophylls are negligible or absent except possibly in a thin surface layer of shallow-water sediments.

The green porphyrin pigments in sediments are a heterogenous group of related compounds as would be expected from their biological origin and from variations in the degree of decomposition of original plant pigments. The more abundant chlorophyll-like pigments in sediments can be extracted from the wet sediments by

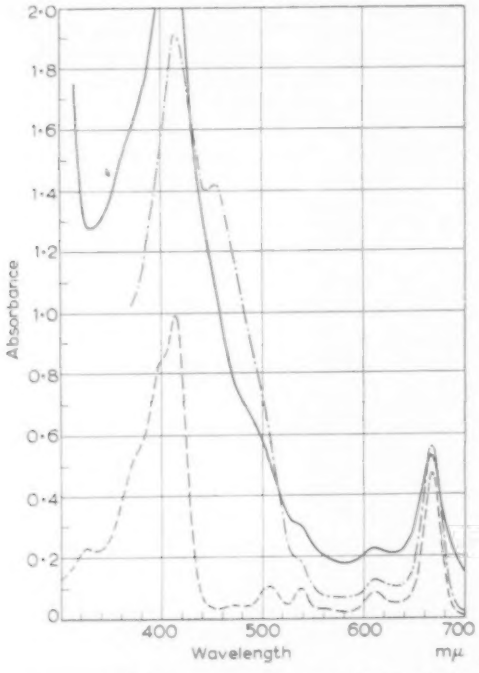

Fig. 1. Typical absorption spectra of sediment extracts and of pheophytin *a* ; chloroform solvent. Basin sediment, ———— ; shelf sediment, — . — . — ; and pheophytin *a*, — — — — — — —.

acetone* and their presence is easily recognized by their strong absorption band in the red region of the spectrum. Carotenoids and other organic materials which are also extracted, absorb light strongly at wavelengths below 550 mμ but cause only a low background absorbance above 600 mμ. Fig. 1 shows the absorption spectrum

*Lesser amounts of other porphyrin pigments are present which require other solvents for extraction. A chloroform extraction, following acetone, extracts only traces of porphyrin pigments – less than 1 per cent of the amounts in the acetone extract. The spectra of a chloroform extract shows a very weak band at about 668 mμ and, in addition, weak bands at about 530 and 570 mμ. The latter peaks are of interest in that they correspond to the absorption bands of the vanadium-porphyrin complexes found in petroleum. The amounts of material, however, have been too small to permit investigation of this possibility. Extraction with cold acetic acid, following chloroform, gives an extract showing a rather wide absorption band at about 655 mμ and a weaker peak at about 600 mμ (spectra in $CHCl_3$). These pigments may amount to 20–25 per cent of those in the acetone extract but their nature has not been investigated. It should be noted that only a few samples have been examined by this series of extractions and these results cannot be generalized.

of typical acetone extracts (in chloroform) from a basin and shelf sediment. The absorption maxima at 668, 611, 535 (shoulder) and 414 mμ are characteristic of phorbines or phorbides derived from chlorophyll *a* (ARONOFF, 1950) This correspondence is shown by comparison of maxima with the curve for pheophytin *a* which is included in Fig. 1. The pheophytin *a* maximum at 507 mμ is usually obscured by the high absorbance of other materials in that portion of the spectrum.

Solvent partition and chromatography allow resolution of the pigments in the acetone extracts into several fractions (all with very similar spectra), but the isolation of pure materials is tedious and can hardly be put on a quantitative basis. In any case such a procedure would be too involved for routine application to a large number of samples. Fortunately, the major pigments have almost identical absorption maxima and the mixtures, therefore, give a fairly sharp maximum at about 668 mμ in chloroform. The maximum generally does not differ appreciably ± 2 mμ) from sample to sample if proper care is exercised in the extraction and handling. The absorbance due to the mixture of chlorophyll derivatives can be determined quite accurately at the red maximum without separation or purification procedures by use of a base line correction for background absorbance.

The conversion of absorbance values into pigment weight offers a difficult problem since the calculation requires the relative amount and absorptivity (extinction coefficient) of each component. Without this detailed knowledge, two alternatives are available : (1) Samples can be compared in terms of absorbance values only, as VALLENTYNE (1955) has done in defining his "sedimentary chlorophyll unit", or (2) the absorbance can be converted to pigment weight by arbitrarily assuming an absorptivity constant which is considered reasonable. The first alternative is more rigorous but the second appears to be a more desirable method of presenting data for geochemical considerations.

Table 1. *Absorptivity constants for pheophytin a in various solvents*

Solvent	*Absorption maximum* mμ	α (l/g cm)	ε (l/mole cm)	*Literature reference*
Chloroform	668	54·4 ± 2·3	4·7 ± ·2 × 10⁴	This work
Ethyl ether	667	62·8 ± 1·4	5·5 ± ·1 × 10⁴	This work
" "	667	60	—	ZSCHEILE and COMAR (1941)
Dioxane	667·5	49.6	4·30 × 10⁴	STERN and WENDELEIN (1936)
Methanol	667	35	3·0 × 10⁴	LIVINGSTON *et al.* (1953)

JASTREBOVA (1938), KLENOVA and JASTREBOVA (1938) and ALDERSHOFF (1951) assumed the absorptivity of chlorophyll *a* for their calculation ; this certainly leads to too low a pigment weight because chlorophyll has a considerably higher absorptivity than any of its degradation products (ARONOFF, 1950). Spectral and chemical properties place these pigments in the group of tetrapyrrols known as phorbines and suggest that the major pigments in marine sediments may be pheophytin *a* and pheophorbide *a*. We have therefore assumed an absorptivity, α, of 50 l/g cm for our calculations. This round figure of 50 is slightly less than the absorptivity of pheophytin *a* as determined in chloroform solution (Table 1).

Preliminary experiments showed that reproducible quantitative determinations were difficult to obtain under a variety of conditions. Previously reported techniques (ALDERSHOFF, 1951 ; JASTREBOVA, 1938 ; KLENOVA and JASTREBOVA, 1938 ; VALLENTYNE, 1955) were not satisfactory if small differences were to be considered, especially for samples of relatively low pigment content. The extraction must be carried out in a short time at room temperature and without excessive exposure to light in order to prevent alteration of the pigments. Decomposition or alteration of pigments is usually indicated by a significant decrease in absorbance and shift of the red maximum to shorter wave length when extracts are allowed to stand overnight or when extended extraction times are used. The volume of acetone required for a sufficiently complete extraction results in a solution which is too dilute for accurate spectral measurement. Concentration by evaporation requires either considerable time or heat and results in precipitation of the pigments because of water extracted from the wet sediment. Concentration by transfer from aqueous acetone to petroleum or ethyl ether gave excessive loss through interfacial precipitates and adsorption on the glassware. However, transfer of the pigments to chloroform minimized these difficulties and a procedure was developed on this basis which is satisfactory for routine use.

MATERIALS

Solvents. Baker and Adamson's Reagent grade acetone and chloroform were used without special treatment Redistilled U.S.P. quality acetone is also satisfactory.

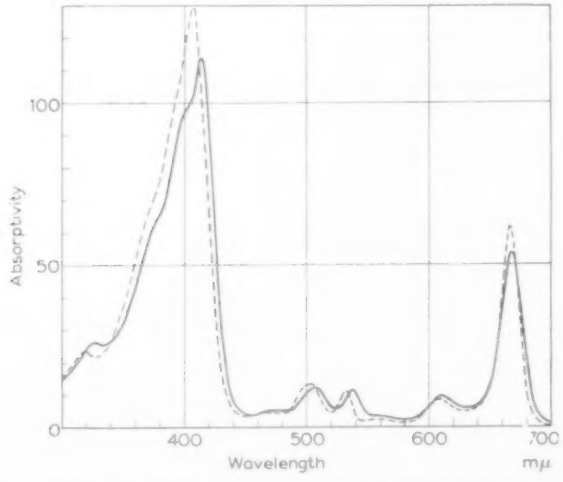

Fig. 2. Absorption spectrum of pheophytin *a* in chloroform (solid line) and ethyl ether (broken line).

Sediment samples. Marine sediment samples were collected off the coast of southern California in basin and non-basin areas. Water depths range from 600 to 2000 m for basin sediments and from beach to deep-sea ($>$ 3500 m) for non-basin samples.

Samples were bottled upon collection and stored at 5°C until used for analysis. An aliquot was taken for moisture determination in order to report the analytical result on the basis of dry sediment. KJELDAHL nitrogen was run on the dry samples as an index of the organic content of the sediment. Samples generally stood less than a month between collection and analysis but it was found that storage for a year did not give a detectable decrease in pigment content.

Pheophytin a. Pheophytin *a* was prepared by the action of hydrochloric acid on standard solutions of chlorophyll *a* in ethyl ether. The technique was similar to that used by LIVINGSTON, PARISER, THOMPSON and WELLER (1953). Chlorophyll *a* was prepared by the method of ZSCHEILE and COMAR (1941).

Absorptivities, α, were determined in ethyl ether and in chloroform. Four determinations were made in each solvent. The average values at the red maximum are given in Table 1 and complete spectral curves are shown in Fig. 2. High accuracy is not claimed for the values because the separate determinations did not show close agreement as indicated by the uncertainties listed in the table. The agreement with the value of ZSCHEILE and COMAR in ethyl ether is satisfactory. Previous reports of the absorptivity of pheophytin *a* in chloroform were not found in the literature, but values reported for other solvents are also listed in the table.

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EXPERIMENTAL METHOD

A weight of wet sediment was selected (according to its estimated pigment content) so that the absorbance at 668 mμ of the total pigment in 100 ml of chloroform would be between 0·2 and 0·8 for a 1 cm light path. This required between 10 and 200 g of wet sediment for most samples.

The wet sediment was placed in a 500 or 1000 ml funnel with a sintered glass disk bottom (medium porosity) and 100 to 300 ml of acetone was added. The funnel was fitted with an efficient electric stirrer from the top, and attached to a 1 or 2 l. suction flask. The acetone and sediment were vigorously stirred for 5–8 min (the longer time for fine grain sediments) and then filtered into the suction flask. A fresh portion of acetone was added and the extraction was repeated. After four extractions, the filtrate was transferred to a 4 l. separatory funnel containing 80 ml of chloroform. About 15 ml of acetone was used to rinse the suction flask and complete the transfer.

Three litres of distilled water was added and the contents mixed very gently. After 60–90 min the aqueous acetone layer was decanted and another 2–3 litres of water added and gently mixed. After the layers were well separated, the chloroform solution was drained into a 1 l. separatory funnel and the aqueous layer discarded. Pigments adsorbed on the large separatory funnel were recovered by rinsing with 10 ml of acetone and added to the chloroform solution. The chloroform solution was then washed twice with about 900 ml of water, drained into a 100 ml graduate, and dried with anhydrous sodium sulphate. The drying agent was removed by filtration through a sintered glass disk funnel into a 100 ml volumetric flask. The graduate, funnel, and drying agent were rinsed with small portions of chloroform and the volume adjusted to 100 ml. A portion of this solution was transferred to a 1 cm corex cell and the absorbance determined in a Beckman DU Spectrophotometer. Generally only the spectral region from 600 to 700 mμ was run. This entire operation was carried out in a semi-dark room.

The pigment content, as parts pheophytin per million parts of dry sediment, was calculated by the formula

$$\text{Pheophytin (p.p.m.)} = \frac{AV \times 10^6}{\alpha\ 1000\ W}$$

where

A = absorbance at maximum (ca. 668 mμ) above a base line from 600 to 700 mμ,

V = volume of chloroform solution in ml,

α = absorptivity of pheophytin *a* in chloroform,

W = weight of dry sediment in grams.

With $V = 100$ and $\alpha = 50$ this reduces to p.p.m. $= (A/W) \times 2000$.

DISCUSSION AND APPLICATION

The procedure adopted represents a compromise between complete recovery and a reasonable time for analysis. Four extractions were shown to recover 97–98 per cent

Table 2. Precision of determination of chlorophyll derivatives in marine sediments as pheophytin a

Sample Number	*Determinations p.p.m. pheophytin in dry sediment*	*Average % deviation from mean*
2622A[a]	70·2 69·0 71·4 70·6 69·0	1·1
3503[b]	104 101	1·7
4743[c]	3·46 3·34	1·8
4744[c]	2·10 2·16	1·4
4745[c]	1·38 1·56	6·1
4746[c]	1·14 1·14	0·0

[a]Santa Barbara Basin core, uniformly mixed sample from 0–100 cm of core.
[b]Santa Barbara Basin core, thin surface sample of approximately 0–1 cm depth of core.
[c]A series of shallow near-shore shelf sediment samples.

of the green pigments which could be obtained by eight or ten extractions. This loss, 2–3 per cent, varies somewhat with the nature of the sediment but is rather constant. Extractions of 5 min each recover as much pigment as 10 min extractions except for very fine grained sediments ; the use of a nitrogen atmosphere during the extraction was found to have no effect on the pigment determination. A slight loss results from discarding the aqueous acetone solution without backwashing with chloroform. However the recovery in a chloroform backwash was found to be less than 1 per cent if the phases are allowed to separate sufficiently in the first extraction. There are always losses due to adsorption on the glassware and the careful rinsing

indicated is quite important. Several experiments were carried out to determine the magnitude of these losses, and in general the incomplete extraction and losses in handling represent about 4 to 6 per cent of the total pigments. Data reported are not corrected for these losses. Duplicate determinations generally agree to better than 3 per cent, even in samples of quite low pigment content (Table 2). The precision of analysis by this technique is better than the reproducibility of sampling marine sediments. The accuracy is of course unknown, largely because of the uncertainty in the appropriate absorptivity constant for the mixed pigments. Nevertheless, the method is more accurate than previously reported techniques and is entirely satisfactory for determining relatively small differences between samples.

The source material of these pigments is considered to be marine plankton, which is known to be rich in chlorophyll *a* and *c* (STRAIN, MANNING and HARDIN, 1943) and may contain small amounts of chlorophyll *d* (MANNING and STRAIN, 1943). Chlorophyll *b*, commonly associated with chlorophyll *a* in land plants, is rare in marine plants except the green algae. No indication of pheophytin *b* has been found in acetone extracts of marine sediments thus far examined (max. ca. 655 mμ). The chemical structures of chlorophylls *c* and *d* have not been established and the properties of their decomposition products are very poorly known. Pheophytin *c* does not have a strong absorption band above 600 mμ and would therefore be difficult to detect without separation from other materials in the extracts. Pheophytin *c* is a pheoporphyrin rather than a phorbine (GRANICK, 1949). Pheophytin *d* has a strong absorption band at 690 mμ and a shoulder or poorly defined maximum has been detected at this wavelength in a few samples. BLUMER (1952) also noted this band in extracts of marine sediments and attributed it to pheophytin *d*. When the 690 mμ band is sufficiently strong, estimates could be made for both pheophytin *a* and *d*. However pheophytin *d* isomerizes into *iso*pheophytin *d* which cannot be distinguished from pheophytin *a* by spectra alone, and the isomerized pigment would therefore be measured as pheophytin *a* by this method.

It can be estimated that more than 99 per cent of the chlorophylls synthesized by plankton are decomposed in the water column and before burial (forthcoming publication). Therefore, the preserved pigments may show no correlation with the relative amounts of the various chlorophylls in plankton because of variations in rates of decomposition of individual pigments.

An attempt is being made in this laboratory to determine the specific chlorophyll derivatives which are major components in the acetone extracts, but conclusive identifications are yet to be made. However, the general properties such as spectra, solubility in organic solvents, and in aqueous acids, are in agreement with the assumption that 90 per cent or more of the pigments are either pheophytin *a* and pheophorbide *a* or closely related phorbines. Characterization of one sample by acid number (FISCHER and STERN, 1940) showed about 70 per cent of the green pigments had acid numbers between 20 and 30, 30 per cent between 14 and 20, and only traces below 14. The acid numbers of pheophytin *a* and pheophorbide *a* are 28–29 and 15 respectively.

Surface sediment samples from marine basins off southern California have been found to range from 4 to 100 p.p.m. of chlorophyll derivatives calculated as pheophytin *a*. Examples are given in Table 3 showing the range of values. The samples are listed in order of increasing depth of water and show a marked decrease in pigment

content with water depth. This trend is a complex function of a number of factors such as (a) plankton production, (b) depth of the water through which the organic particles must settle, (c) oxygen content of the bottom water, (d) sedimentation rate which determines the time of exposure on bottom before burial and (e) the total organic content of the sediment which is not independent of the other factors. Detailed discussion of these data will be published elsewhere.

Table 3. Chlorophyll derivatives (as pheophytin a) in California basin sediments

Location[a]	*Sample number*[b]	*Basin depth* (m)	*Depth in sediment*[c] (cm)	*Pheophytin p.p.m. in dry sediment*	*% Nitrogen in dry sediment*
Santa Barbara Basin	3503	598	0–1	103	0·355
San Pedro Basin	4646A	800	0–4	24·8	0·308
	4646B	"	0–5	21·6	0·319
Santa Monica Basin	4647A	899	0–8	46·8	0·378
	4647B	"	0–14	46·6	0·357
	3414	914	0–10	57·0	—
	3501	910	0–3	58·4	0·421
San Diego Trough	4666	1250	0–5	31·7	0·437
	4667	1210	0–5	13·5	0·424
Catalina Basin	3736	1311	0–1	34·4	0·544
Tanner Basin	4696A	1510	0–8	41·5	0·664
	4696B	"	0–1	35·4	0·702
West Cortes Basin	4674A	1595	0–3	10·4	0·408
	4674B	"	0–8	8·1	0·351
East Cortes Basin	4671A	1675	0–5	9·3	0·393
	4671B	"	0–5	7·2	0·370
San Clemente Basin	4669	2060	0–5	6·0	0·398
	4672	1940	0–8	3·6	0·262

[a]See EMERY and RITTENBERG (1952) for description of basins and sediments.
[b]Numbers which are identical except for A and B are samples from the same station collected in the pilot and piston cores at the same lowering.
[c]It is difficult to obtain undisturbed surface layers. Depths listed are best possible field estimates.

Sediment cores have been examined to determine the variations with depth in the sediments. Variations in pheophytin with depth show changes in sedimentation conditions with time which correlate with changes in nitrogen, carbonate and grain size of the sediments. An appreciable decomposition of pheophytin after burial is also indicated in the nearshore basins. For example, the Santa Barbara Basin contains 103 p.p.m. of pheophytin in the top zone (0–1 cm), only 57–76 p.p.m. in the zone between 2 and 200 cm and between 25 and 45 p.p.m. from 400 to 500 cm. The deeper offshore basins show little indication of decomposition of pheophytin with depth of burial. Where a significant decomposition of pigments occurs with depth of burial or time, it must result either in the formation of other porphyrins — of different solubility and/or spectral properties — or in destruction of the porphine nucleus. The porphyrins found in petroleum may be formed in small amounts during this early decomposition but evidence of their presence is lacking. However this may be, it can be concluded that adequate amounts of suitable source materials are preserved in most of these sediments for subsequent conversion into the chlorophyll type porphyrins found in petroleum.

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Department of Geology, University of Southern California

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Measurements of southern swell at Guadalupe Island*

W. H. MUNK and F. E. SNODGRASS

(*Received* 24 *June* 1957)

Abstract—We have obtained some energy spectra of pressure fluctuations on the sea bottom at a depth of 60 fathoms off Guadalupe Island, Mexico. The spectra consist of peaks whose frequency increases by about 10 per cent per day ; sequences repeat once every three or four days. The waves come from the southwest quarter, and the distance of generation is estimated at 8000 nautical miles. The signals are attributed to cyclones in the storm belt of the Southern Hemisphere. The earliest arrivals are of the order of 1 mm high and 1 km long. They may have originated in the Indian Ocean and passed just east of New Zealand, or to the west through the Tasman Sea. Later arrivals were generated in the South Pacific. Measurements taken at many other occasions at various localities in the north-east Pacific indicate that this radiation from the Southern Hemisphere is present at all seasons. Apparently it constitutes the principal background in the ocean wave spectrum for the low frequencies under consideration.

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A HISTORICAL NOTE

THE photograph shown in Fig. 1 was the first indication of southern swell reaching the coast of California. Allowing for refraction in shallow water the off-shore direction was computed to be south south-west, and it was inferred that the waves had originated in a storm area in the southern oceans (HYDROGRAPHIC OFFICE, 1944). The photographed wave pattern is remarkably regular; it looks almost like the single-frequency, long-crested train of sine waves used in elementary oceanographic texts and advanced mathematical treatises to portray ocean waves. A distant origin could account for the regularity. The wave direction would be nearly uniform (i.e. the waves are long-crested) inasmuch as a distant storm subtends a small angle, and the range of frequency would be small because of the sorting of frequencies by dispersion. Fig. 1 was the first of a long series of aerial photographs we took during the war, and it must be added that in no subsequent photograph did we observe quite as regular a wave pattern.

The problem of the propagation of ocean waves was not at all well understood until BARBER and URSELL (1948) succeeded in obtaining spectra of ocean waves. In nearly all of forty case histories they were able to trace prominent frequency bands to storms in the north Atlantic Ocean, but on at least two occasions they found unmistakable evidence that the swell had been generated in storms occurring beyond the limits of this ocean. In one case they first noted a spectral band peaked at a period of 21 sec at 1100 hr on 14 May 1946, and this period decreased uniformly (except for a frequency modulation by tidal currents, which confirmed the southern origin) to 15 sec on 19 May. We shall make references to the following quotation from BARBER and URSELL's (1948) paper :

"... there appears to be at least one significant discontinuity in the trend

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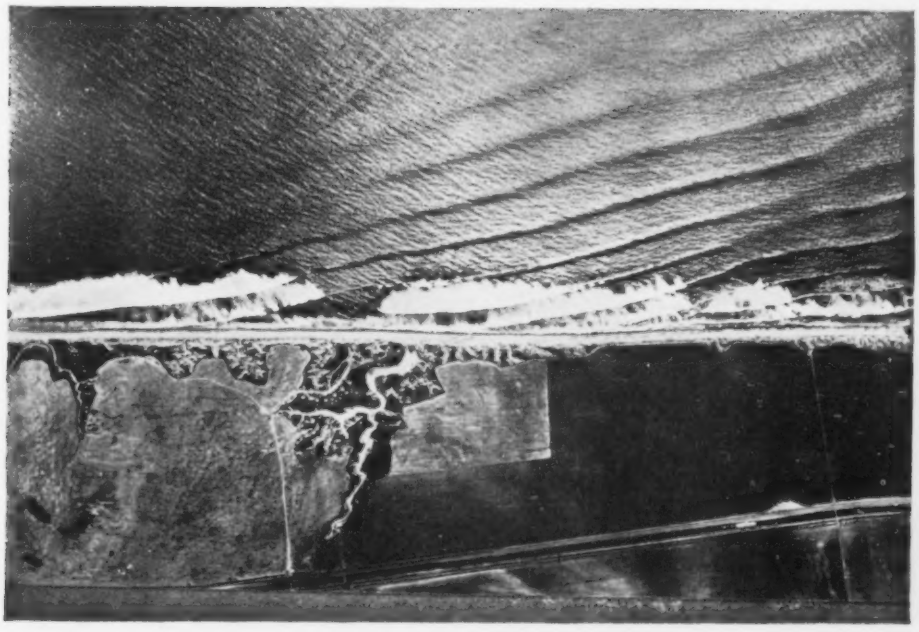

Fig. 1. Aerial photograph of waves at Camp Pendleton, California, on 16 January, 1944. The coast trends north-west – south-east.

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> of maximum periods ; after 1700 hr on 16 May the spectra suggest that the frequency is widened by the arrival of swell whose maximum period is 2 to 3 sec longer than the mean maximum of the previous spectra. A second widening at the upper end of the frequency band possibly occurs at 1900 hr on 19 May when there is some, though not very reliable, indication of activity at periods up to 23 sec."

BARBER and URSELL compute the distance of origin from the observed frequency shift, and arrive at 6000–7000 nautical miles : " the storm must, therefore, be sought in the southern ocean, probably in the Falkland sector to which there is an open great circle course from Land's End". The meteorological evidence available was too scanty to be very helpful. The maximum height of the southern swell was 30 cm.

DONN (1949) has discussed wave spectra taken at Cuttyhunk and Bermuda. He notes that

> " The periodograms frequently show a unique wave signature exactly at the 15 sec mark. This group may show a range of from 14 to 18 sec, with occasional extensions slightly beyond these limits. From a study of many records it appears that this group is nearly always present, but at times may become too small to be detected, even by harmonic analysis."

Allowing for appropriate travel time, DONN has compared the Cuttyhunk and Bermuda spectra and concludes that the waves come from the south.

> " Assuming this southerly origin, weather maps of the belt of the westerlies of the Northern and Southern Hemispheres have been studied at length. No such swell source appears possible from transitory cyclones and anticyclones of either hemisphere. In addition the " window " of approach from possible storms in the South Atlantic is extremely restricted. The suggestion is thus offered here that this swell group is generated by the South-east trade winds. This seems to be the only source that would explain their constancy."

J. E. DINGER (personal communication) has remarked on a 15–16 sec hump in the spectra of waves at the Barbados. RUDNICK (1951) finds 15–20 sec bands in spectra of waves at Guam.

WIEGEL and KIMBERLEY (1950) obtained (without frequency analysis) the " significant " height and period of the predominant waves recorded at Camp Pendleton, California, and conclude that they originate in the area between 40° and 65°S and 120° and 160°W. The largest recorded period during a summer season was 22 sec.

OFF-SHORE RECORDING

For the last two years we have used a Vibrotron transducer (SNODGRASS, MUNK and TUCKER, in press) to record fluctuations in bottom pressure at depths varying from 80 to 300 m. Twenty-four stations have been occupied on the continental shelf and borderland off southern California. At *all* stations, regardless of season, we have noted a pronounced regular oscillation, such as shown in Fig. 2. The recorded periods (mean interval between crests) varies from 14 to 20 sec, wave heights (root mean square values corrected for depth) from 10 cm to 1 m. In the majority of cases the periods were between 15 and 16 sec.

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Out first attempt to determine wave direction was by comparison with simultaneous visual observations conducted at Camp Pendleton (see Fig. 1) by Warrant Officer BOYD, U.S.M.C. The visual observations include breaker angle and littoral current ; these parameters are notoriously unreliable for determining off-shore wave direction, but they were the only means available. All that can be said is that on such days when the shore observations indicated waves from the south-west quarter, their height and period were consistent with the values recorded offshore.

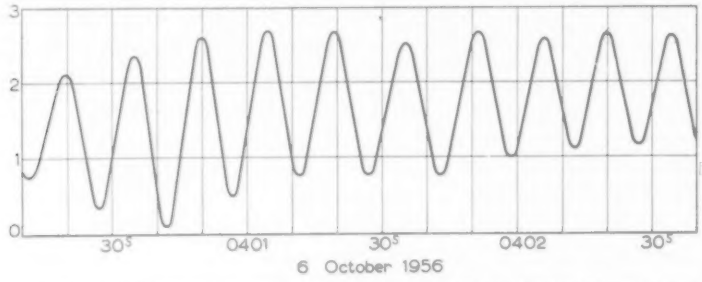

Fig. 2. Short section of Vibrotron record at the protected station of Guadalupe Island. The scale gives inches of water pressure on the sea bottom.

On 25–27 June we attempted to use the wave "shadow" behind San Clemente Island as a means of estimating wave direction. We first occupied a station at the north-west end of the island, which is exposed to waves from the south-west quarter, followed immediately by a station at the east side, which is protected from this quarter. The results were :

	June, 1954	*Period* (sec)	*Height* (cm)
San Clemente, West	25, 1300 hr	14·8	64
	25, 2300	14·4	59
	26, 0500	13·8	77
San Clemente, East	26, 1100	14·6	15
	27, 1400	14·1	10

On 3–8 October 1956 we occupied two stations at Guadalupe Island, 200 nauticat miles off the coast of Mexico and well off the continental borderland. The firsl station was protected from the south-west quarter, the second station was not. At the exposed station the waves were four times higher.

The evidence, while not conclusive, points to a southern origin of the low-frequency signal. Our observations differ from previous work on account of the great depth at which they were taken. Depth acts as a low-pass filter ; local disturbances are of higher frequency, and attenuated accordingly. The result is that low frequency signals were prominent at all times in these filtered records, and at such times as we could check, a southern origin was indicated.

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GUADALUPE SPECTRA

Fig. 3 shows seven successive spectra of the Guadalupe wave records. The following information is recorded :

Guadalupe Island, north station, 29°09′·30N, 118°16′·35W. Depth : 113 m				
1956	m	N	f	95% limits
(1) 3 Oct., 2220 – 4, 0500	62	6000	194	0·82 – 1·24
(2) 4 Oct., 1020 – 4, 1700	62	6000	194	0·82 – 1·24
(3) 4 Oct., 2220 – 5, 0500	62	6000	194	0·82 – 1·24
(4) 5 Oct., 1020 – 5, 1700	62	6000	194	0·82 – 1·24
(5) 5 Oct., 2220 – 6, 0500	62	6000	194	0·82 – 1·24
Guadalupe Island, south station, 28° 50′·55N, 118°16′·45W. Depth : 109 m				
(6) 7 Oct., 1236 – 7, 2142	62	8190	261	0·84 – 1·21
(7) 7 Oct., 2142 – 8, 0648	62	8190	261	0·84 – 1·21

Bottom pressure was recorded every 4 sec, and successive values were harmonically analysed on an electronic computer, following the method of TUKEY (1949). We obtained $m = 62$ estimates of energy density, of which 25 values are plotted (without smoothing). The degrees of freedom $f = 2N/m$ determines the statistical reliability of the estimates. For spectra (1) to (4) there is only one chance in twenty that the true energy density is less than 0·82 or more than 1·24 times the computed value. Tides were removed prior to analysis by numerical high-pass filtering. The plotted curves are surface spectra ; the depth of the instrument has been allowed for according to hydrodynamic theory. The many details of the analysis have been described elsewhere (MUNK, SNODGRASS and TUCKER, in press).

The characteristic feature of the spectra is the progressive shifts of individual peaks from low to high frequencies. The peaks emerge at about 50 cycles per kilosecond (period 20 sec) and their frequency increases by something like 7 per cent per day until they disappear in the locally generated spectrum. The energy of the peaks reaches a maximum around 65 c/ks. The history repeats itself at an interval of 3 to 4 days. This behaviour is in accord with the remarks by BARBER and URSELL quoted earlier. There is a sharp increase in one of the peaks from record (4) to (5). We return to this later.

The essential point is that we have analysed records from 25 to 30 times longer than those previously used (except for two isolated analyses by RUDNICK, 1951) and that the resolution is improved accordingly. Thus the spectrum between 40 and 90 c/ks is described by 25 estimates of energy density, rather than just a very few values of less reliability. The spectra available to DONN were of such poor resolution that progressive spectral peaks, if present, could not have been discerned, and the signals would appear as a steady " hum " at 15 sec. The observed steadiness has lead DONN (1949) to suggest generation by the steady south-east trades rather than by transitory storms to the south. The British results, and those obtained at Guadalupe, suggest that the Bermuda spectra could likewise reveal a fine structure of progressive peaks if the records were analysed with adequate resolution.

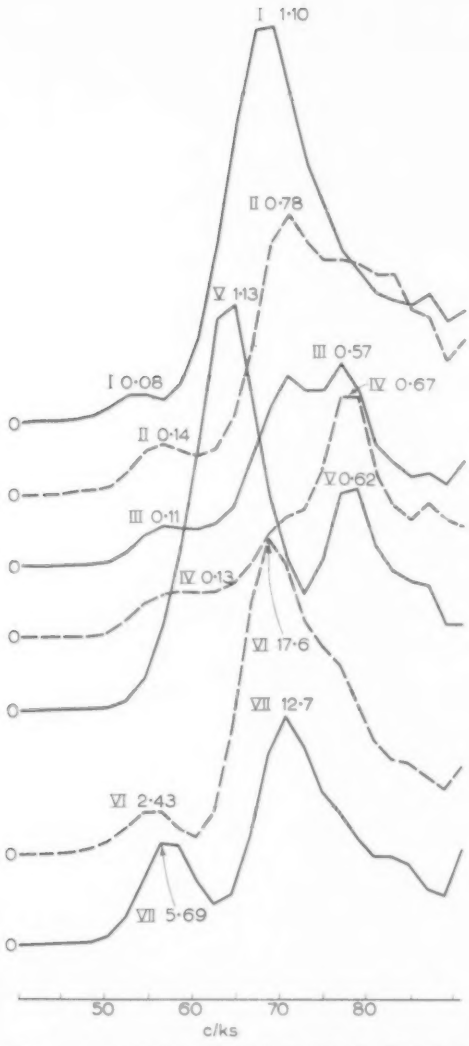

Fig. 3. Energy spectra of waves recorded at Guadalupe Island. The frequency scale is in cycles per kilosecond (or millicycles per second); the ordinate gives "energy" density in cm² per c/ks on a sliding scale. Zeroes and peak values are indicated. The last two spectra are drawn to one-twentieth scale.

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WAVES FROM A SINGLE IMPULSIVE SOURCE

A distance-time diagram is useful (Fig. 4, bottom). Suppose that at some distance r_0 from the recording station, and at some time t_0, a sudden concentrated disturbance generates waves over a broad band of frequencies. Any elementary wave train of

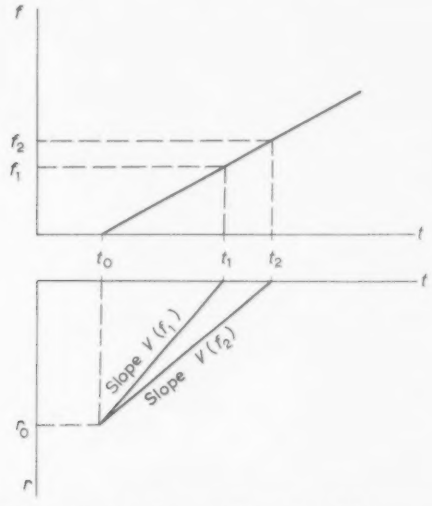

Fig. 4. Frequency-time and distance-time diagrams for an impulsive source at a distance r from the wave station, and time t_0. Two particular frequencies, f_1 and f_2, arriving at the station at times t_1 and t_2 respectively, are characterized by the rays of slope $V(f_1)$ and $V(f_2)$ on the r, t-diagram.

frequency f, travelling at the appropriate group velocity $V = g/(4\pi f)$, is characterised by a " ray " in the r, t-diagram extending from the source (r_0, t_0) to the receiver (O, t) with slope $V(f)$, where

$$V = \frac{r_0}{t - t_0} = \frac{g}{4\pi f}. \tag{1}$$

The mathematical foundation of this simple geometric construction has been summarized by ECKART (1948). The requirement is that the different velocities of the Fourier components have dispersed the disturbance into a well-resolved spectrum.

BARBER and URSELL (1948) have constructed such " propagation diagrams " to locate the source of the recorded waves. Let the spectrum of waves arriving at time t_1 reveal a narrow band peaked at frequency f_1, and at a later time t_2 a peak at a higher frequency f_2. Then the rays drawn through the points 0, t_1 and 0, t_2 with the slopes V_1 and V_2 as given by equation (1) intersect at a point which determines the distance and time of the source. In one case five rays covering the interval 14–18 May 1946 give a good intersection for a point at a distance 6000 miles from the recording station, at a time 6 May 1946.

An equivalent construction has been used by MUNK (1947). Equation (1) can be written in the form

$$f = \frac{g}{4\pi r_0}(t - t_0) \tag{2}$$

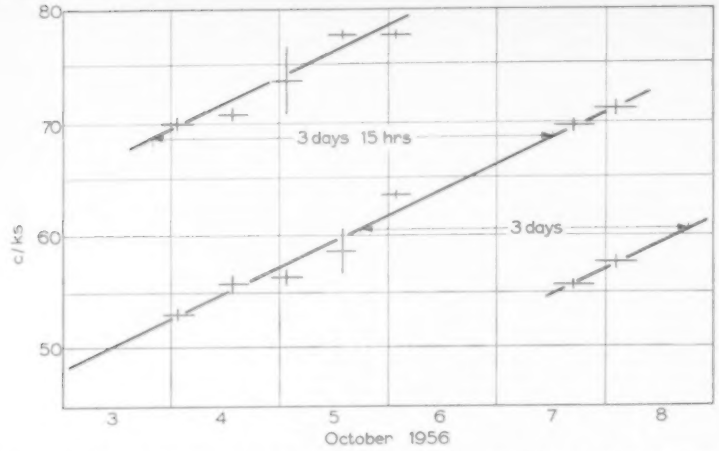

Fig. 5. Frequency-time diagram for the Guadalupe Spectral peaks, Fig. 3. Each frequency band is indicated by a cross. The vertical lines give a measure of the possible range of values of peak frequency; the horizontal lines give the duration of the analysed record.

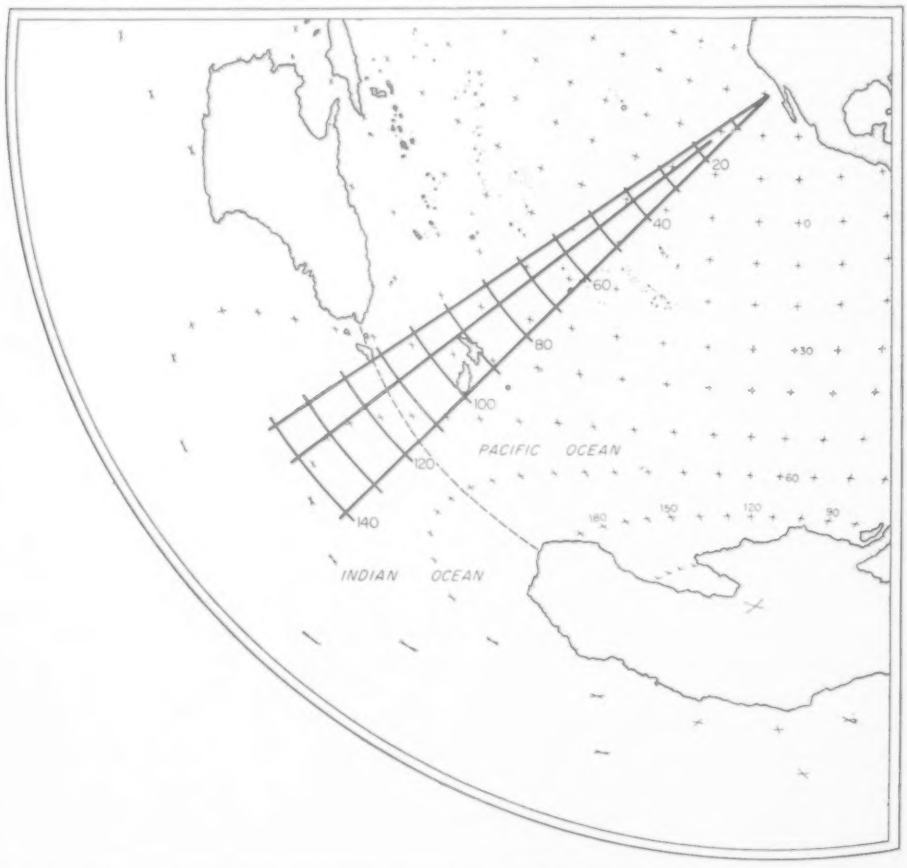

Fig. 6. Azimuthal-equidistant projection centred on San Diego. Distances from Guadalupe are given in units of degrees (1° equals 111 km).

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so that the frequencies from a point source lie along a straight line in a frequency-time diagram (Fig. 4, top). The intercept determines t_0 and the slope gives r_0. The Guadalupe spectral peaks have been fitted by straight parallel lines on an f, t-diagram, (Fig. 5). There are three sequences, separated by 3 days 15 hr ; and by 3 days respectively. If we insist in fitting all sequences by parallel lines, we obtain a single value, $r_0 = 135°$ (15,000 km). This places the source in the Indian Ocean (Fig. 6) The values of t_0 are 18 Sept. 1956, 1900 hr ; 22 Sept., 1000 hr ; 25 Sept., 1000 hr. Conceivably we might ignore the last two values inasmuch as they were taken at another station, and draw a steeper line. The smallest value of r_0 is about 110°, and the t_0 times are later, but by no more than 1 day 17 hr.

But one is led immediately to question the validity of seeking an instantaneous point source. A travelling storm will be many days along an unobstructed path from the time it passes south of Australia. We are naturally led to generalize the construction.

WAVES FROM A MOVING POINT SOURCE

A storm is moving eastward at some constant rate W along colatitude c (Fig. 7). Then

$$\phi R \sin c = Wt \tag{3}$$

is the storm's distance from a point P just south of the station. R is the Earth's radius. The storm's longitude ϕ and the time t are taken as negative when the storm

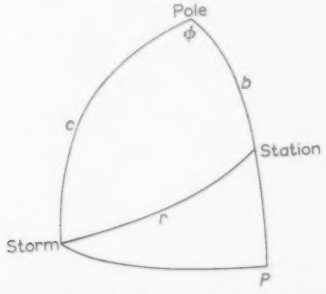

Fig. 7. b and c are polar angles of station and storm referred to the pole nearest the station. P is a point south of the station at co-latitude c.

is west of the station, as shown in the figure. The great circle distance from storm to station* is rR, where

$$\cos r = \cos b \cos c + \sin b \sin c \cos \phi. \tag{4}$$

It is convenient to interpret ϕ also as dimensionless time according to (3). Fig. 8 shows the storm track on an r, ϕ-diagram. The storm is nearest the station when $\phi = 0$ and furthest when $\phi = 180°$. The inflection point is of particular interest. Setting $d^2 r/d\phi^2 = 0$ gives two solutions :

$$\cos r_I = \frac{\cos b}{\cos c}, \qquad \cos \phi_I = \frac{\tan c}{\tan b}, \qquad \frac{dr}{dt} = \frac{W}{R}, \qquad \text{for } b + c > 180° \tag{5a}$$

*This presumes that waves travel along great circles. ECKART finds (personal communication) that because of the earth's rotation there will be an angular deflection of the order (wave period/½ day)^2 or 10^{-7} for 20 sec waves. The deviation from the great circle route is then of the order of 1 m.

$$\cos r_i = \frac{\cos c}{\cos b}, \qquad \cos \phi_i = \frac{\tan b}{\tan c}, \qquad \frac{dr}{dt} = \frac{W}{R}\frac{\sin b}{\sin c}; \qquad \text{for } b + c < 180^\circ \tag{5b}$$

In the first case the wave station is no further north of the equator than the storm is south of the equator (or vice versa). There exists then a great circle route through the station and tangent to the storm's latitude. At the point of tangency the storm moves east with the same speed as it moves towards the station ; $R \cdot dr/dt = W$. In the second case the station is further north than the storm is south, and the rate of approach of the storm towards the station is always less than W.

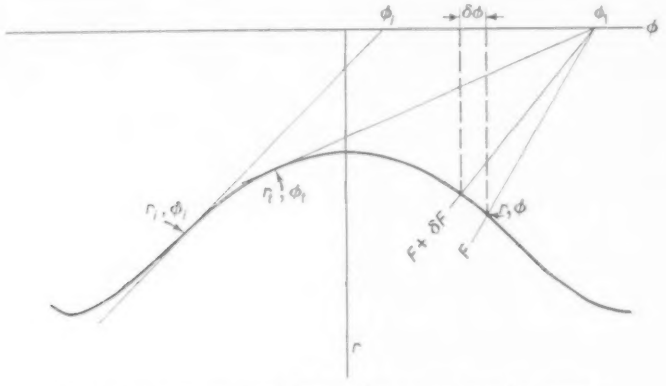

Fig. 8. A distance-time diagram for a moving point source.

Consider a " ray " from ϕ, r to ϕ_1, 0 (Fig. 8). This ray represents the travel of an elementary wave train having left the storm at time $t = (R \sin c/W)\,\phi$ and arrived at the station at $t_1 = (R \sin c/W)\,\phi_1$, thus having covered a distance rR with a group velocity

$$V = \frac{rR}{(R \sin c/W)\,(\phi_1 - \phi)}.$$

A convenient notation is $f_0 = g/4\pi W$ for the frequency corresponding to a group velocity W. In view of (1)

$$F = \frac{f}{f_0} = \frac{W}{V} = \frac{(\phi_1 - \phi)\sin c}{r}. \tag{6}$$

For any (dimensionless) frequency F recorded at time t_1 the distance and longitude of generation are determined by the intersect of the ray with the storm's track on the r, ϕ-diagram. There may be zero, one or three intersections. For the tangent ray (Fig. 8)

$$F_t = -\frac{\sin r_t}{\sin b \sin \phi_t} = \frac{(\phi_1 - \phi_t)\sin c}{r_t}. \tag{7}$$

Let $E(F)$ designate the " energy " spectrum of the wave record. The contribution to the mean square elevation from frequencies in the range F to $F + \delta F$ is denoted by $E(F)\,\delta F$. This contribution $E(F)\,\delta F$ comes from a segment of the storm track that is subtended by the rays associated with F and $F + \delta F$, respectively (Fig. 8).

Let $\delta\phi = [W/(R \sin c)]\, \delta t$ be the projection of this segment upon the ϕ-axis. The storm is presumed to radiate energy at a uniform rate*, and $E(F)\, \delta F$ is proportional to $|\delta t|$, and hence to $|\delta\phi| \sin c$; it also varies as the energy density $S(F)$ of the generation spectrum, inversely with r because of dispersion, and inversely with $\sin r$ because of angular spreading (see, for example, LAMB, 1932, pp. 432-433). Nothing is known about attenuation, and we neglect it. Hence

$$E(F)\, \delta f \sim S(F)\, |\delta\phi| \sin c/(r \sin r)$$

$$E(F) = \mu S(F), \qquad \mu = \frac{|\delta\phi/\delta F| \sin c}{r \sin r} \tag{8}$$

where $\mu(F)$ may be regarded as the energy amplification, operating on the generation spectrum $S(F)$ to give the recorded spectrum $E(F)$. The evaluation is a problem in differential geometry (see Appendix), but in general terms the result is evident from Fig. 8 : (1) For any given time t_1 (hence ϕ_1) μ is sharply peaked for the particular ray through r_t, ϕ_t tangent to the storm track ; (2) the tangent ray through the inflection point r_i, ϕ_i gives a peak of all such peak values. The foregoing argument is related to the method of stationary phase.

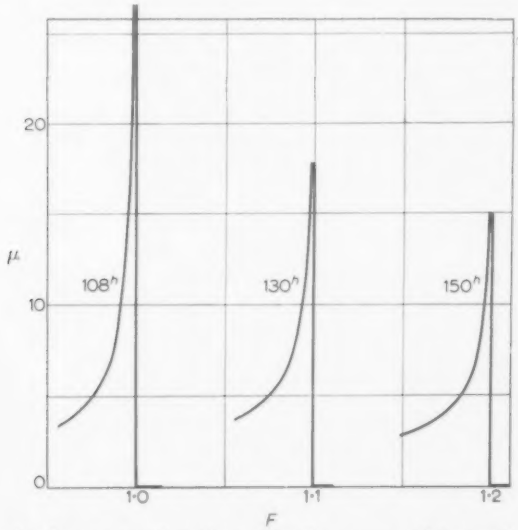

Fig. 9. The amplification factor at various times *after* the passage of the moving point source to the south of the station (point *P*, Fig. 7), the first " tangent arrival " through the inflection point is more amplified than successive tangent arrivals.

Fig. 9 has been drawn according to equation (15). Near the tangent ray μ approaches infinity as $(F - F_t)^{-\frac{1}{2}}$ except near the inflection point. Then $F_t = 1$, and $\mu\ (= \mu_i)$ approaches infinity as $(F - 1)^{-\frac{1}{2}}$. Though the spikes are infinite, the area under the spikes is finite. If the generation spectrum $S(F)$ is a smooth function, estimates of the energy density in the frequency interval $F_t - \Delta F$ to F_t can be written

*One may think of the storm as a series of momentary disturbances, each sending out an identical dispersive train. The *number* of disturbances contributing to $E(F)\, \delta F$ is then proportional to $|\delta t|$.

$$\int_{F_t-\Delta F}^{F_t} E\mu \, dF = E \int_{F_t-\Delta F}^{F_t} \mu \, dF = 2h\,(\Delta F)^{\frac{1}{2}} E, \qquad \text{(tangent ray)}$$

$$= 3h_i\,(\Delta F)^{\frac{1}{3}} E \qquad \text{(inflection ray)}$$

as compared to something of the order $(\Delta F)\,E$ away from the spikes. The *recorded* peak amplifications

$$2h\,(\Delta F)^{-\frac{1}{2}}, \qquad 3h_i\,(\Delta F)^{-\frac{2}{3}} \tag{9}$$

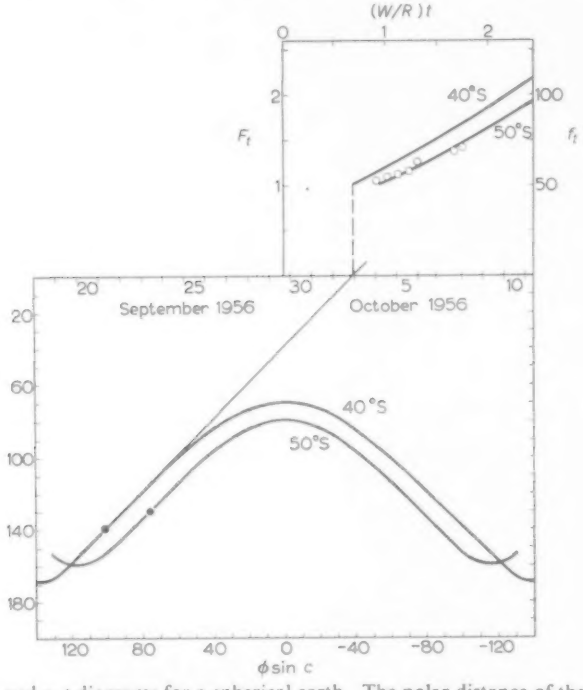

Fig. 10. The f_t, t- and r, t-diagrams for a spherical earth. The polar distance of the station is taken as $b = 61°$, corresponding to Guadalupe Island. The diagrams are drawn for the travelling point source at 40° and 50° S. The inflection points are marked and one of the tangents is drawn. The curves in the upper figure gives F_t against $(W/R)\,t$ for the two assumed latitudes of generation. The scales in real time and in frequency units c/ks have been drawn for $W = 30$ knots. The observed points are for the middle sequence of spectral peaks (Figs. 4 and 5).

depend upon the frequency *resolution* ΔF and will be large if the resolution is high, i.e. ΔF is small. In our work Δf is 4 c/ks, $f_0 = 50$ c/ks, hence $\Delta F = \Delta f/f_0 = 0{\cdot}08$ (equation (6)). Fig. 9 is drawn for $b = 61°$ (co-latitude of Guadalupe), $c = 140°$, $W = 30$ knots. For the tangent ray through the inflection point, and two subsequent tangent rays, we have

F_t	1·0	1·1	1·2
t_1	$108h$	$130h$	$150h$
r_t	130°	107°	100°
ϕ_t	− 118°	− 82°	− 70°
h_i, h, h	0·41	0·78	0·64
Equation (9)	6·7	5·7	4·7

The conclusion is that at *any* time the energy density of the frequency corresponding to the tangent ray is amplified, but that the earliest of all possible tangent rays (the

inflection point ray) is amplified more than subsequent tangent rays. We might then expect the observed spectral peaks to correspond to these tangent rays. In physical terms, the prominent waves are those whose group velocity equals the rate of approach of the storm toward the station somewhere along its path.* The existence of such a " group velocity peak " has been noted by ECKART (1953) for waves generated by a moving gust, and is implicit in his equation (35).

The constructions in Fig. 10 are for storms 40°S and 50°S and the wave station at 29°N. The computed f_t, t-curves in the upper figure are obtained by drawing tangents to the storm paths to where they intersect $r = 0$. The cotangent of the angle between $r = 0$ and the tangent line equals F_t at the time given by the intersection. The observed points correspond to the central sequence of spectral peaks. For a storm path along 50°S the storm was at the inflection point on 23 Sept., 0800 hr at a distance of 130°. The waves were recorded $4\frac{1}{2}$ days *after* the storm had passed to the south of the station. This is hardly synoptic information ! The computed distance of generation is similar to that derived for an assumed point source. We conclude that according to the present hypothesis of a moving point source the earliest arrivals of swell observed off North America originated in the Indian Ocean at a distance of 120–140° (Fig. 6).

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DISCUSSION

We have attempted to interpret the Guadalupe spectra on the basis of two hypotheses, both severely oversimplified : (1) generation by an instantaneous point source ; (2) by a point source moving with constant speed along a fixed latitude. Both hypotheses lead to wave trains of gradually increasing frequency but for altogether different reasons. In the case of (1) the increase in frequency is due to dispersion; i.e. low frequencies travel faster than high frequencies, and arrive earlier. The essence of the moving-point hypothesis is that one frequency is amplified over all others : that frequency whose group velocity equals the rate at which the storm approaches the station (tangent rays on a distance-time graph).

The gravest observed frequency (from the first arrivals) are likewise determined by quite different considerations. In hypothesis (1) the limit is imposed by the generation spectrum : winds of velocity U cannot effectively generate waves whose *phase* velocity C exceeds U. In the latter case the *group* velocity $\frac{1}{2}C$ of the first arrivals is determined by the storm's rate of approach. In general this is less than the storm's rate of travel, W, unless the storm is moving along a great circle route towards the station. For an east-west movement there is a point where a great circle through the station is tangent to the storm's latitude circle, and the amplified frequency, $g/(4\pi W)$, is the gravest possible (the " inflection ray " on the distance-time graph). Suppose the storm is at 50°S ; the great circle through the station can be drawn only if the station is south of 50°N. If it is north of 50°N then the gravest frequency is somewhat less than $g/(4\pi W)$ in accordance with equation (5b). Thus the gravest frequencies are of the order

$$g/(2\pi U) \text{ or } g/(4\pi W)$$

*OLIVER and EWING (1957) apply similar considerations to account for the observed increase in the frequency of waves and microseisms from hurricane Dolly. They refer to LAMB's discussion of the ship wake problem, being able to neglect the earth's curvature on account of the proximity of the storm.

according to the two hypothesis. Typical values for Antarctic cyclones are $U = 50$ knots, $W = 30$ knots. Both criteria lead to frequencies of the order of 1 cycle in 20 sec, as observed.

All of this discussion depends, of course, upon the existence of unobstructed great circle routes. One unobstructed great circle can be drawn from Guadalupe passing just east of New Zealand and tangent to 55°S at a point in the Indian Ocean 130°E longitude (see Fig. 6). Another great circle can be drawn through the Tasman Sea tangent to 50°S at a point in the Indian Ocean south of Western Australia. These regions are among the stormiest in existence. The window through the Tasman Sea is narrow, and the waves must be scattered by South Pacific islands. A storm moving eastward would be " seen " only briefly through the Tasman Sea window, and a proper hypothesis might be some combination of the instantaneous and moving source hypotheses. In all events, the observed frequency shift by less than 10 per cent per day is consistent only with very distant areas of generation, regardless of which of the two hypotheses is followed, and the estimated distance of 130° is consistent with either of the two routes. It is therefore tentatively suggested that the very low, long early arrivals came from the Indian Ocean. We are puzzled by the sharp increase in the spectral peak on the morning of November 6 (see Fig. 3), corresponding to the fifth point of the central sequence (Figs. 5 and 10). The corresponding tangent ray gives a distance 100° for the storm at 50°S. Could this represent an arrival of an unobstructed wave train from a storm passing over New Zealand into the Pacific Ocean ?

N. F. BARBER has kindly examined the weather maps drawn by the New Zealand Meteorological Office for the period in question. Unfortunately the meteorological situation was not clear-cut. The computed travel times are in doubt by, say $\pm$ 20 per cent or $\pm$ 2 days, and no definite correlations can be made. A 30–35 knot wind over a fetch of 500 nautical miles on 17 Sept. 1957 centred at 140°E is consistent with a route to the east of New Zealand, and may have been responsible for the central sequence. We prefer to postpone any detailed comparisons with meteorological data until the International Geophysical Year. For that purpose we are establishing a wave station west of San Clemente Island which will include a measure of wave direction and beam width in addition to the features discussed in this paper.

For the British records there is no unobstructed great circle corresponding to the inflection point arrival. Setting $b = 40°$, $c = 140°$, $\phi = -50°$ gives $r = 108°$,

$$(dr/dt)/W = \sin b \sin c \sin \phi = 0{\cdot}47$$

for the earliest unobstructed tangent arrivals. The corresponding frequencies of something like 100 c/ks are much higher than those observed for the first arrivals. In the case of the Bermuda records any unobstructed southern storm is east of the station, and receding from it. The tangent ray hypothesis is therefore inapplicable to the Atlantic records, and this detracts from its attractiveness. There is the possibility that reflection from ocean boundaries is an important factor, especially for the very long, low initial arrivals.

There has been no discussion as to why the spectral bands should reach their maximum development at frequencies of about 65 c/ks, or concerning the existence of a steady 15–16 sec "hum", if such a hum does in fact exist. In an average taken over many storms, the effect of the amplification spikes (Fig. 9) is erased, and an

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explanation must be sought along different lines. The generation spectrum is peaked at frequencies significantly higher than 65 c/ks, but it is possible that the shift toward lower frequencies resulting from selective attenuation may account for the observed values.

Acknowledgements—We are indebted to F. PETERSON, M. J. TUCKER and JOHN SWALLOW for their part in the Guadalupe measurements. DOROTHY SHUMWAY and MARGARET COVHER have been largely responsible for programming and carrying out the numerical analyses on the computer facilities at Convair, San Diego, and we are greatly indebted for the use of these facilities. CARL ECKART and MOHAMED HASSAN have given advice with regard to the problem treated in the appendix. We are also indebted to N. F. BARBER and C. PALMER for discussion and advice.

University of California
Scripps Institution of Oceanography, California

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APPENDIX

The problem is to evaluate

$$\mu(F) = \frac{\sin c}{r \sin r F'} \tag{10}$$

near the tangent ray

$$r_t' = r_t/x_t, \qquad x = \phi - \phi_1. \tag{11}$$

The accent denotes differentiation with respect to ϕ (or x), and the subscript " t " refers to evaluation at the tangent point. ϕ_1 and ϕ_t are constants. Differentiating $F = -x \sin c/r$ (equation (5)) and using $r_t' x_t = r_t$ leads to

$$F_t' = 0, \qquad F_t'' = x_t r_t^{-2} r_t'' \sin c, \qquad F_t''' = x_t r_t^{-2} r_t''' \sin c. \tag{12}$$

To evaluate F' we eliminate ξ from the Taylor expansions

$$F = F_t + \xi F_t' + \tfrac{1}{2}\xi^2 F_t'' + \tfrac{1}{6}\xi^3 F'''_t,$$

$$F' = F_t' + \xi F_t'' + \tfrac{1}{2}\xi^2 F_t'''.$$

For the ordinary tangent ray the last term for each series is dropped, and $F_t' = 0$. The result is

$$F' = [2(F - F_t) F_t'']^{\frac{1}{2}}. \tag{13}$$

But for the tangent ray through the inflection point $r_t'' = F_t'' = 0$. Eliminating ξ now gives

$$F' = (9/2)^{\frac{1}{3}} (F - F_t)^{\frac{2}{3}} (F_t''')^{\frac{1}{3}}. \tag{14}$$

The admittance factor μ can now be evaluated in terms of x and r making use of (12) :

$$\mu^{-2} = 2 \sin^2 r_t (F - F_t) x_t r_t''/\sin c,$$

$$\mu_i^{-3} = (9/2) \sin^3 r_t (F - F_t)^2 x_i r_t r_t'''/\sin^2 c.$$

Differentiating equation (4) and using (7) and (5a) leads to

$$r_t' = -\sin c/F_t$$

$$r_t'' = \sin b \sin c \operatorname{cosec}^2 r_t (\sin r_t \cos \phi_t - r_t' \cos r_t \sin \phi_t)$$

$$r_i''' = r_i' (r_i'^2 - 1), \qquad r_i' = \sin c,$$

so that finally

$$\mu = h (F - F_t)^{-\frac{1}{2}}, \qquad \mu_i = h_i (F - 1)^{-\frac{1}{2}} \tag{15}$$

where

$$h^{-2} = 2 r_t \sin b (\cos r_t \sin \phi_t + F_t \sin r_t \cos \phi_t/\sin c)$$

$$h_i^{-3} = (9/2) \cot^2 c \, r_i^2 \sin^3 r_i.$$

INSTRUMENTAL NOTE

Nylon rope for deep-sea instrumentation

(*Received* 9 *May* 1957)

NYLON rope (density 1·1) has advantages over a steel cable (density 7·8) when used at great depths due to (1) the weightlessness of the nylon in the water, (2) the elasticity of the nylon (20 per cent at breaking strength) and (3) the ability to " feel " when the instrument has encountered the bottom.

Experiments were made with nylon braided rope on the *Calypso* off Cape Mattapan, Greece (1955) in one of the deepest known spots in the Mediterranean. It was found that a 50 kg weight on a $\frac{1}{4}$ in. nylon braided line required 35 minutes to reach 2250 fathoms. The line was then used to anchor a small metal boat which served as a radar buoy so that a sonar survey could be made of the area.

Because of the elasticity, the nylon should be rewound on the take-up reel after the stress due to the pull-up cycle has been relieved.

Further tests were made from the *Calypso* in 1956, especially in the Romanche Trench (0° 10′S, 18° 21′W) at 4100 fathoms. Here a camera and electronic flash lamp were lowered twice to the the bottom on a $\frac{1}{4}$ in. nylon braided line manufactured by the Samson Cordage Company. The bottom was reached in about 2 hours. The line became slack when the camera (about 100 lb) touched the bottom. The breaking strength of the line was about 1300 lb.

The *Calypso* was anchored for about three days at this spot over the Romanche Trench on a $\frac{1}{8}$ in. nylon braided line of about 4000 lb breaking strength, using two anchors connected by a 50 ft length of chain. The anchor and line were not recovered. It is believed that the anchors were stuck in rocks. A rocky bottom is shown in the two photographs that were obtained.

One of the photographs shows a brittle star. Both photos show numerous white objects of about 1 in. length that are off the bottom by about 1 in. distance. One of these creatures has several hairs of about one inch long extending from one end of its body. This one animal was photographed against a dark background caused by the shadow of a rock ledge.

Free descent time is approximately, for a $\frac{1}{4}$ in. line,

$$t = \tfrac{2}{3}\sqrt{\frac{k}{w}}\,x^{3/2}\ \text{sec}$$

where

$k = 3 \times 10^{-4}$ pound sec^2/ft^3,

x = length of the cable in the water in feet,

w = weight of instrument in pounds.

The deepest ocean depths, 36,000 ft, can be reached in about 2 hours with a 150 lb camera. The friction of the nylon line in the water is the predominating resistance producing effect.

The French Ministry of Education, the National Geographic Society and the Massachusetts Institute of Technology have sponsored this project. Mr. CRAWFORD GREENEWALT donated funds for nylon rope.

Professor of Electrical Measurements, Massachusetts Institute of Technology, Cambridge, Mass. HAROLD E. EDGERTON

Directeur, Institut Océanographique, Musée de Monaco, Monaco, Principauté JACQUES Y. COUSTEAU

Former students, Massachusetts Institute of Technology JOHN B. BROWN and ROBERT H. HARTMAN

LETTER TO THE EDITORS

WE HAVE available a number of prints of a new nomogram, designed to compute σ_t from salinity and temperature of sea-water. This nomogram is designed to cover observations in the N. Atlantic, and the scales extend from 33–38‰ in salinity and from − 2–18°C in temperature. It is, of course, suitable for any other observations within these ranges.

The precision of the computation is better than 0·01 in. σ_t over the whole range. Actual results compared with the calculated figures show a mean deviation of 0·002. The dimensions of the sheet are 26 × 20 in.

We think this nomogram will be useful to all workers who have numerous density figures to compute. It has, of course, the advantage over tables of working equally well in reverse, for computing salinity or temperature from density. Copies of the nomogram may be obtained from the librarian, National Institute of Oceanography, for 2s. 6d. each, including postage.

National Institute of Oceanography,
Wormley, Nr. Godalming, Surrey

R. A. Cox

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IN MEMORIAM

Harald Ulrik Sverdrup (1888–1957)

On 21 August 1957, Harald Ulrik Sverdrup died in Oslo from a heart attack, only two days after the death in Stockholm, also by heart failure, of his close friend Carl-Gustaf Rossby. The era of the explorer-scientist from the countries of the large Coriolis force is drawing to an end.

Sverdrup came from a family of churchmen. His maternal grandfather, Ole Vollan, was a parish-verger in Bergen's cathedral and one of the political leaders in the liberal party; his paternal grandfather, a minister of the church, had five sons who became ministers and three daughters who married ministers. His father was professor of theology at the University of Oslo when Sverdrup enrolled there as student in "Physical Oceanography and Astronomy". His early interest was in astronomy, but this changed when he received one of the renowned Carnegie assistantships to Professor V. Bjerknes. During the next six years he published twenty papers, largely in dynamic meteorology. His doctoral dissertation, *Der nordatlantische Passat*, represents the first attempt towards energy and momentum budgets of the North Atlantic trade winds. The use here of mathematics as a tool for quantitative description rather than deductive reasoning is typical also of his later work.

At the age of 29, Sverdrup took charge of the scientific work on Roald Amundsen's North Polar expedition, with additional duties as navigator and part-time cook. The expedition ship *Maud* left Norway in July 1918, planning to come home in three years. Sverdrup did not return to Norway until December 1925. Winter after winter the ship was frozen fast, and the goal to duplicate the drift of the *Fram* (with his relative, Otto Sverdrup, as Captain) was never realized. Nevertheless, the collected observations represent one of the few significant records of the Arctic. These include astronomic and meteorologic observations, measurements of tides, currents, the physical properties of sea-water and of sea-ice, studies in marine geology, aurora polaris, gravity, magnetism, atmospheric electricity, even some observations concerning animal and bird life on the drift ice. At one time Sverdrup left the ship to spend eight months as a lone white man with the nomadic Chukchi tribe of north-eastern Siberia, an experience he later reported in a delightful popular book.* The most significant of the *Maud* papers, *Dynamics of Tides on the North Siberian Shelf*, was completed for publication during the last winter in the Arctic, without adequate literature and without the benefit of discussion. Only sea-going oceanographers can appreciate this feat. Yet, the achievement of which Sverdrup was most proud is not scientific: after seven years on the *Maud* he parted friends with all his shipmates.

Upon his return, Sverdrup succeeded V. Bjerknes in the Chair of Meteorology at the Geophysical Institute in Bergen, Norway. In 1931, he became research professor at the Christian Michelsen Institute in Bergen. The two appointments enabled him to devote most of his efforts from 1925 to 1935 towards a general account of the expedition and to publish fifty papers on the diverse observations. During this decade he also spent two half-year periods in Washington to participate in the analysis of oceanographic data collected on the seventh cruise of the *Carnegie*. In 1928 he married Gudrun Bronn Vaumund. In 1931 he took charge of the scientific work on the Wilkins Ellsworth North Polar Expedition aboard the submarine *Nautilus*, and in 1934 Sverdrup spent two months with the glaciologist H. W. Ahlmann in the high-lying snow fields of Spitzbergen and published the first quantitative heat budget of glaciers. These ten years (1925–1935) following the *Maud* expedition were the most productive of a productive scientific career.

In 1936 Sverdrup accepted, for a limited period, the Directorship of the Scripps Institution of Oceanography, at La Jolla, California, and accordingly took leave of absence from the Michelsen Institute for three years. But the war intervened and he did not permanently return to Norway until 1948. The Scripps Institution then had thirty employees in all and no sea-going vessel. Sverdrup

*An English translation by Sverdrup entitled *Reindeer Hair in Your Soup* has unfortunately not been published.

persuaded Mr. Robert Scripps to donate the schooner *E. W. Scripps* and initiated a study of the Gulf of California and of the waters off southern California. At the outbreak of the war, the *E. W. Scripps* was diverted to Navy studies, and again the Institution was left landlocked. Sverdrup laboured hard in an attempt to remedy this situation. Near the end of his tenure an opportunity arose of financial support for work in California waters to study environmental factors related to the fluctuation in the population of the California sardine and of other pelagic fishes. Sverdrup seized this opportunity with both hands and initiated the Marine Life Research Program, a program active at Scripps today.

The twelve years in California presented Sverdrup with the first opportunity to teach, an activity he enjoyed and did exceedingly well. His effectiveness as a teacher came largely as a result of his modesty and warm personal interest in human beings. He made colleagues of his students rather than subordinates. Among his students and younger collaborators were Roger Revelle, Richard Fleming, Robert Arthur, Don Pritchard, Robert Reid, Gifford Ewing and myself. By the end of the war, the need for more trained physical oceanographers had become evident, and Sverdrup organized the first systematic course in oceanography given in the United States. This was attended by several dozen officers of the armed forces. All of us will remember how Sverdrup entertained us at his home with stories of the Chukchi tribe and demonstrations of his physical fitness (e.g., standing on his head at the age of sixty).

During the pre-war years Sverdrup devoted much effort to write, in collaboration with Martin Johnson and Richard Fleming, a comprehensive 1100-page volume, *The Oceans, their Physics, Chemistry and Marine Biology*. I consider Chapter 15 of *The Oceans* . . . , entitled " The Water Masses and Currents of the Oceans", as Sverdrup's outstanding scientific achievement. At the outbreak of the war, Sverdrup worked on problems dealing with underwater sound. Later he developed current charts for life rafts and methods for predicting sea and swell for amphibious landings. He was glad for the opportunity to throw his great energy and knowledge behind the war effort. The invasion of his native land and the death of one of his brothers while engaged on a Commando raid had brought great sorrow to him. After the war he favoured co-operation with scientists from all countries, including the U.S.S.R., as a contribution towards world peace. Ironically he was called a red stooge in a California paper and a pawn of American imperialism in a communist paper of Norway, both articles appearing at about the same time. He was undisturbed by these attacks; he had lived according to his convictions and, in his own words, " that was that". I feel that these unhappy incidents must be recorded; they shed as much light on the man as his scientific contributions. Palmén in a recent letter characterized him as a "sällsynt gedigen person". This means something like "an out of the ordinary sterling person", but the Swedish expression is far more precise and striking.

In 1948, at the age of sixty, Syerdrup returned to Norway, He greatly admired Nansen's decision to drop all scientific research at this time of life and had told me he would do the same. He did. And, like Nansen, he embarked upon new activities which were as important and interesting as his earlier ones, As Director of the Norsk Polar Institutt, he was engaged at the time of his death in organizing that institute's activity during the International Geophysical Year. He was President of the International Council for the Exploration of the Sea and preparing for the fall meeting in Bergen. He was in charge of Norwegian activities for improving fisheries in India. He was Prorector of the University of Oslo and Director of the Summer School for foreign students at the University. He was also Chairman of a committee for re-organizing the Norwegian educational system; a task to which he had held for many years in spite of difficulties and disappointments.

A small stroke in spring gave warning that he was taxing himself too hard. Like Rossby, he chose to ignore the warning and to serve full strength till the hour of his death.

W. H. MUNK

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BOOK REVIEWS

Second International Seaweed Symposium. Edited by T. BRAARUD and N. A. SÖRENSEN, Pergamon Press, London and New York, 1956. 220 pages. 60s. $9·00.

THE Second International Seaweed Symposium, held in Trondheim in July 1955, was organized by the Norwegian Institute of Seaweed Research and the forty papers there presented by scientists and industrialists from fifteen maritime countries reflect the world-wide interest in this new branch of applied science.

An indication of their scope may be obtained from the index which shows that ten papers dealt with the chemical composition of seaweeds and the structure of certain algal chemicals, fourteen were concerned with botanical studies and eleven covered investigations directed towards seaweed utilization. The remainder were concerned with microbiology and analytical methods.

Two-thirds of the papers read are recorded in full, the others are in abstract form the main data being published elsewhere.

With the discussions, which take about one-tenth of the space, the variety of subjects covered is too wide for individual mention. A few, however, for one reason or another, linger particularly in this reviewer's mind: the elegance of GEERT ANDERSEN's work at the Institutt für Meereskunde, Kiel, on the birefringence properties of alginic acid; the clear exposition by J. HØIE of his painstaking study with Ø. SANDVIK at the Agricultural College of Norway of the value of seaweed meals for chicks and laying hens, and the delightful descriptions of seaweeds of economic importance in Southern China by MISS BEK-TO CHIU.

It is encouraging to find that, of the ninety "active" members of the Symposium (all of whom are listed with their addresses) nearly one third were technologists or industrialists. One of the latter, R. G. GARDNER, who reported the results of fundamental work on his seaweed drying equipment at the Royal College, of Science and Technology, Glasgow, was rewarded with the largest and liveliest discussion of any. Other papers which attracted extended discussion dealt with X-ray and infra-red studies on carragheenin, the carotene content of Norwegian seaweeds, the production of antibiotics by marine algae, the production of mannitol and laminarin from seaweed aqueous extracts and the growth rings of *Alaria* stipes.

The diagrams and photographs are excellently reproduced and the format of the book leaves nothing to be desired. Professors BRAARUD and SÖRENSEN, besides taking a leading part in the organization of the Symposium, have proved themselves to be excellent editors of its proceedings.

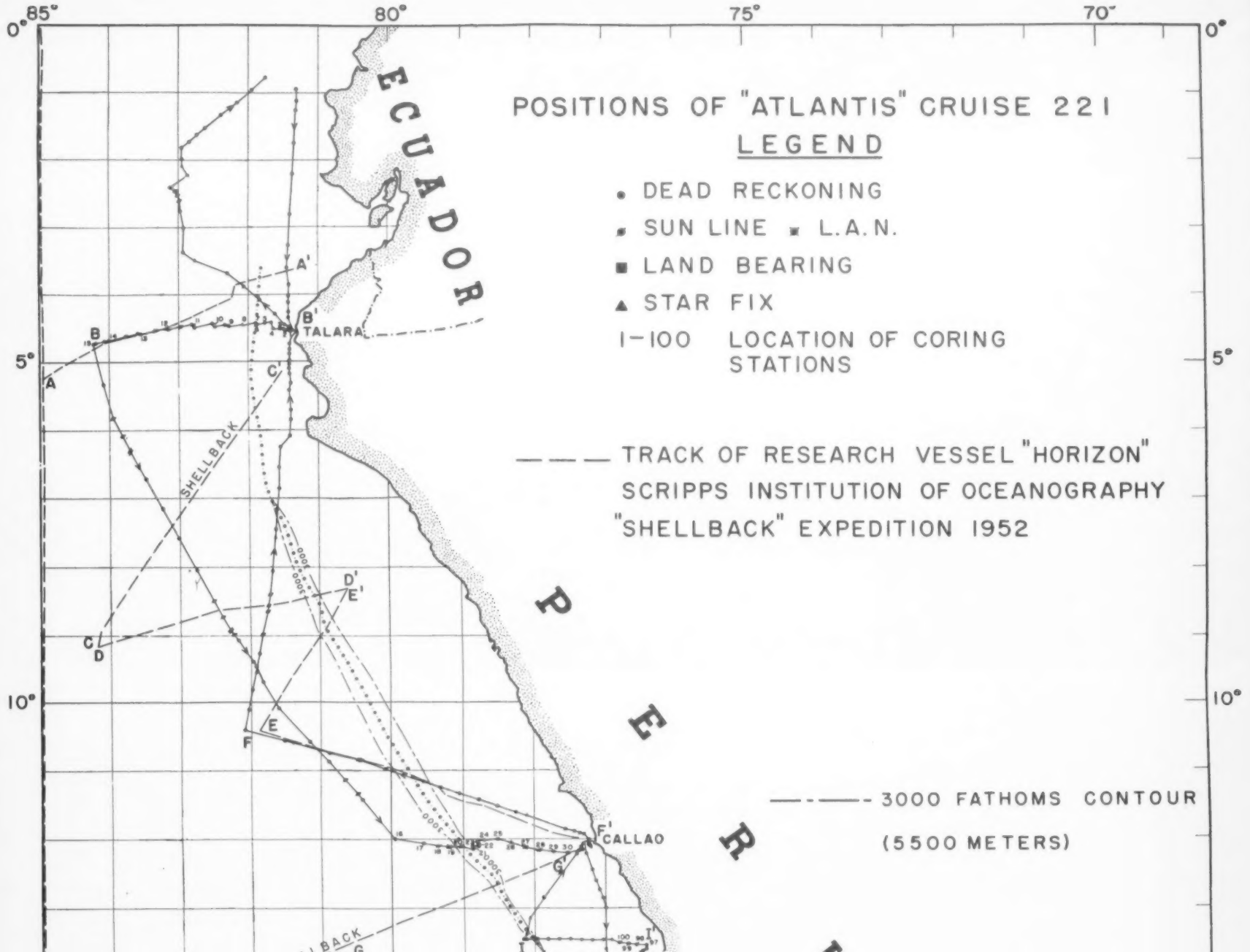
The Third International Seaweed Symposium is planned to be held in Galway, Ireland, on the 13th–19th August, 1958, and if the papers read there prove to be of the same high quality as those at the first two symposia, it will be an event of considerable importance to those interested in this new field of scientific endeavour.

F. N. WOODWARD

Oceanic observations in the Pacific 1949. University of California Press 1957. 363 pp., 6 charts.

EVERY physical oceanographer must be well aware that the literature dealing with oceanic observations leaves much to be desired. It is often a work of some magnitude even to discover whether any observations have been made in an area. Ideally, one would like to be able to feed a geographical location into some machine and get back a complete set of the available data.

In the absence of such a system this book (intended to be the first of a series) fills a useful, if small, place. The information is clearly presented and seems commendably free from typographical errors, and the charts, though on rather a small scale, are easy to read and make location of the desired data


POSITIONS OF "ATLANTIS" CRUISE 221
LEGEND
• DEAD RECKONING
SUN LINE ▪ L.A.N.
■ LAND BEARING
▲ STAR FIX
1–100 LOCATION OF CORING STATIONS
TRACK OF RESEARCH VESSEL "HORIZON"
SCRIPPS INSTITUTION OF OCEANOGRAPHY
"SHELLBACK" EXPEDITION 1952
3000 FATHOMS CONTOUR
(5500 METERS)
ECUADOR
PERU
TALARA
CALLAO
SHELLBACK
0°
5°
10°
85°
80°
75°
70°

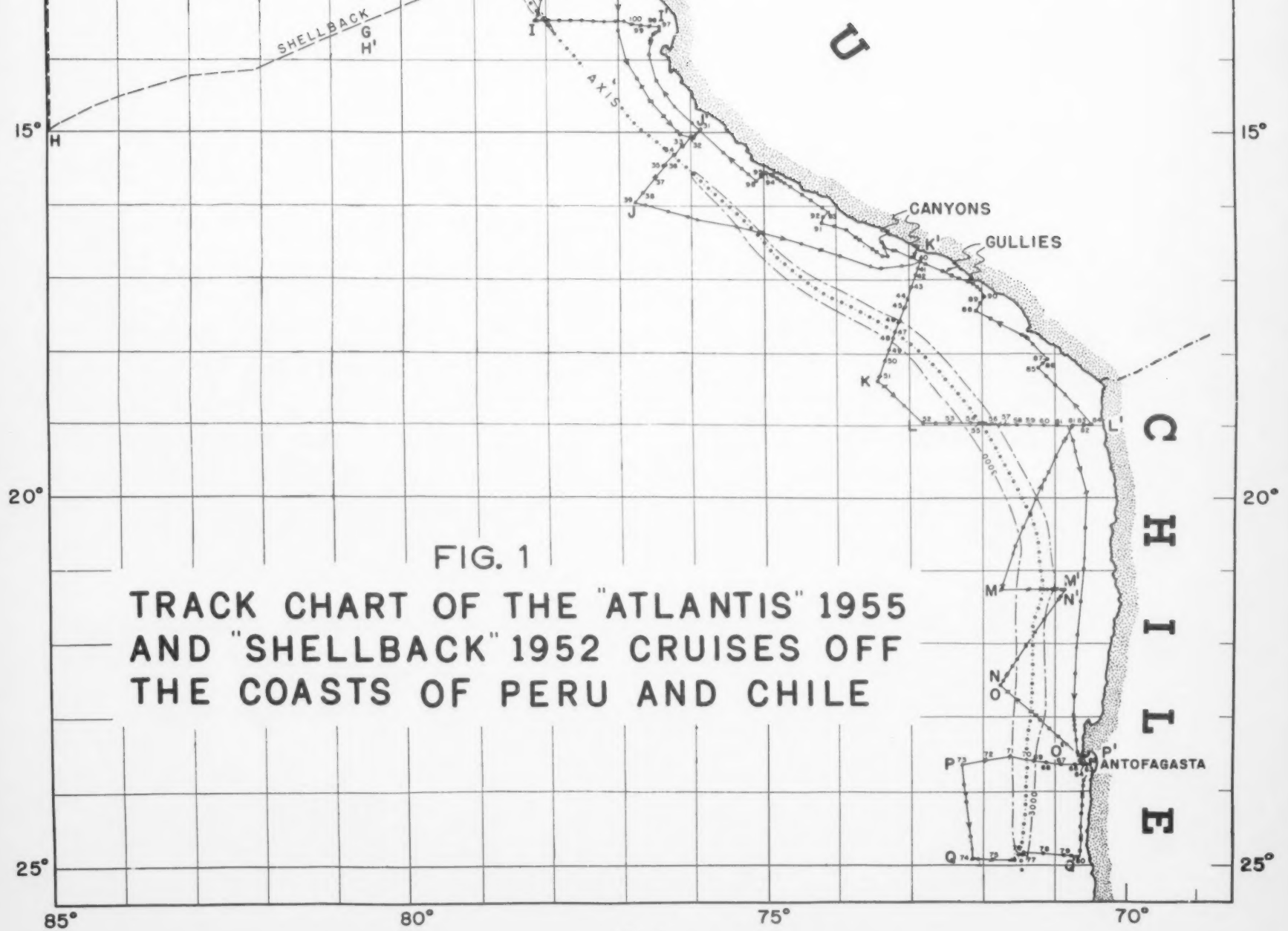


FIG. 1

TRACK CHART OF THE "ATLANTIS" 1955 AND "SHELLBACK" 1952 CRUISES OFF THE COASTS OF PERU AND CHILE

Fig. 1.

simple and rapid. The methods used in computing the figures, and the chemical techniques, are however indicated only by references to other papers. It might be supposed that one of the principal functions of this type of book would be to save the labour of referring to original papers, which may not be readily available. A page or two in the introduction summarising these techniques would have meant little extra work for the editors, and saved much for others. It is also unfortunate that no reference is made under the station details to the biological work carried out, or to any special measurements which were made.

In the preface the editors express a hope that other workers in the Pacific will use future volumes for publication of their data. This would be a great advance, and I suggest that even if it is not possible for financial reasons to include full details of work in other countries it would still be very useful to include a station chart of such work, with indications to where the details may be found.

R. A. Cox

ERRATUM

Deep-Sea Research, 4 202–210 The beryllium-10 concentration in deep-sea sediments by P. S. Goel, D. P. Kharkar, D. Lal, N. Narsappaya, B. Peters and V. Yatirajam.

Line 8 of the Abstract: *for* $2{\cdot}55 \times 10^{10}$ *read* $2{\cdot}55 \times 10^{6}$.

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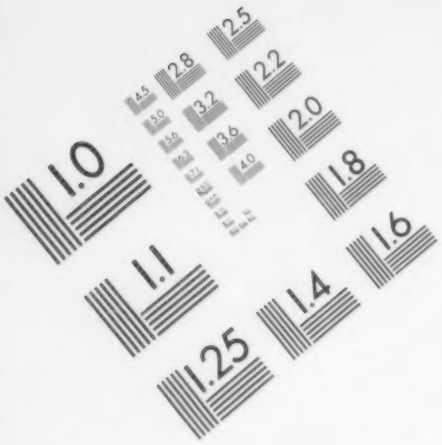

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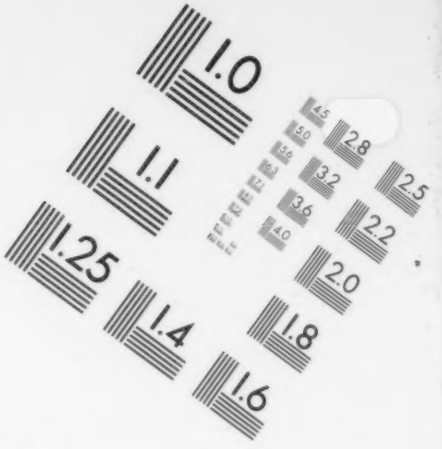

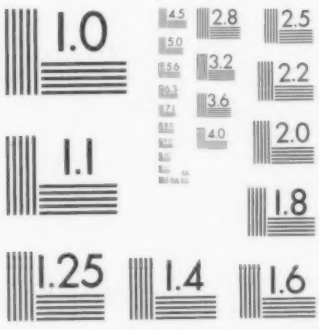

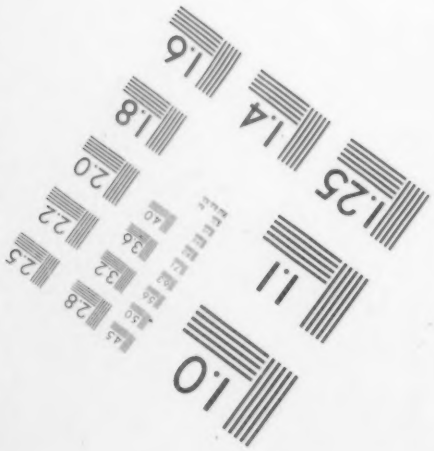

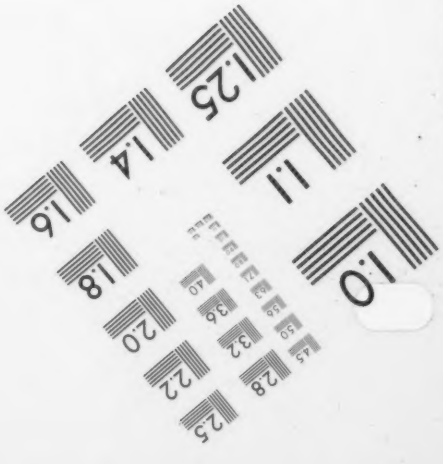

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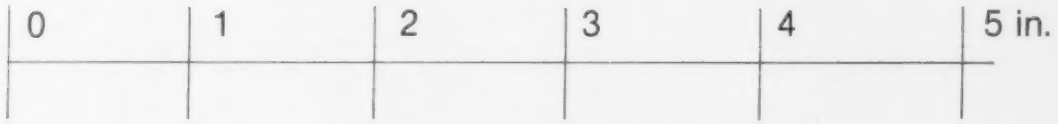

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